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A Sensitivity Analysis of the Hydrology of the Bow Valley above Banff, Alberta using the UBC Watershed Model

Phase II

Final Report

by

G.J. Young

Wilfrid Laurier University

to

Government of the Province of Alberta

Department of Environmental Protection

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Acknowledgments

Most of the work presented here, as Phase II of the Bow Valley Study, was undertaken by Alexi Zawadski and represents a part of his MES thesis. Without Alexi's enthusiasm and diligence it would have been nearly impossible to complete the study.

A debt of gratitude is owed to Dr Michael Quick, of the University of British Columbia, for allowing use of his UBC Watershed Model in running the simulations presented in this study.

Corinne Schuster worked for several weeks to produce the final version of the report.

The author acknowledges the contributions of all these co-workers and also acknowledges the support given by several other students who were peripherally involved in parts of the study.

Gordon J Young, Wilfrid Laurier University, July 1998.

1. Executive Summary

Mountain regions are important sources of water for adjacent, relatively dry regions. Such is the case in the Alberta Rockies. The Bow Basin above Banff is a typical Rocky Mountain watershed (almost completely unaffected by human activities), providing significant water supplies for the Calgary and southern Alberta region.

The basic components of mountain hydrology are fairly well understood. In the case of the Bow River the snowmelt component of flow dominates the hydrograph; rainfall and water derived from glacier wastage are significant, but of lesser general importance. Losses of water due to evapotranspiration can be significant and the delay in runoff due to storage as groundwater and in lakes is reasonably well understood. It is well known that during the last several decades glaciers have been in retreat. Over the long term the contribution to flows waters derived from glacier recession must reduce. It is this component of the flow which is examined in this report.

A very important caveat is that assumptions made about climatic trends in the future are, at best, good estimates. To the extent that we cannot confidently predict the climates of the future, speculation on the future river flows is inexact.

The report summarizes the characteristics of the Bow Basin above Banff and describes the current knowledge of the hydrology and meteorology of the region. Many details of the hydrology are still unknown, but it is believed that the major components and interrelationships are adequately understood.

The UBC Watershed model is used in the report as the basis for hydrological simulations. It allows changes in the extent of glacier cover to be input and also allows input of various climate scenarios for the future. It thus allows us to ask "what if" questions. What if the glaciers were to retreat by 30% or 62% from their current extent (taken as 1993 extent)? What if climate changed such that winter and summer temperatures and precipitation changed significantly? Would the hydrology be significantly altered?

The year 1969 was taken as the most "average" year as possible from a meteorological standpoint. Its meteorological record was input to the basin with a 30%, a 62% and a 100% reduction in glacier size. *The findings from this simulation are very important for, as might be expected, while total annual flows are reduced by relatively small amounts (4.7%, 6.7% and 8.2% respectively), the July - August flows are reduced by 13.1%, 17.2% and 21.9% respectively. These are highly significant reductions.* Furthermore it should be noted that in dryer than normal years the summer flows would be expected to be reduced to much greater extents. *Thus in years of high water stress, the loss of glacier contributions as a result of recession would be highly significant in the summer months.*

It should be noted that none of the 4 climate scenarios applied to the watershed involved a reduction in precipitation or a reduction in mean annual temperatures. Thus, as might be expected, overall reductions in flows are not predicted in the simulations; however, *significant changes in the regimes of flow are predicted.* These may be significant for some water users.

While caution should always be exercised in making hydrological predictions, it is safe to conclude from this study that further reduction in glacier extent is highly likely to reduce summer flows in years of lower than normal precipitation. Such reductions will likely be highly significant to already stressed water users.

2. Introduction: Glaciers and a Changing Climate

The influence of the "Little Ice Age" on the global distribution of glaciers began to diminish around the middle to the end of the last century, when global temperatures once again began to increase. In response, alpine glaciers retreated to higher elevations as the hydrologic system moved towards an equilibrium with the changing climate (Meier, 1984; Oerlemans, 1987). It should be noted that there were some exceptions to this generalization in Scandinavia and Patagonia (Holmlund and Fuenzalida, 1995).

Glaciers in the Canadian Cordillera were among those that retreated (Henoch, 1971; Luckman, 1990). Quantitative observations of the retreat of Yoho Glacier were first made in 1906 (Wheeler, 1934), and further recessional observations of Peyto, Chaba, Helmet, Sentinal and Sphinx glaciers were made in the 1920's and 1930's. (McCoubrey, 1937). Ice recession in this region has been extreme and virtually uninterrupted to the present day, however, this trend cannot continue indefinitely. If the climate continues to warm as suggested and precipitation remains relatively unchanged, glaciers will retreat further to higher elevations or sheltered areas and the potential for glacier runoff will decrease as their areas decrease in size.

In order to assess the effects of climate change on glacier mass balance and subsequent basin hydrology, two general parameters need to be identified (Kuhn, 1993): the present hydrometeorological conditions for runoff in a snow and ice covered basin must be established (daily and seasonal hydrographs need to be explained by spatial and temporal variations of the snow and ice covers and energy inputs); and the nature of the expected climate change needs to be defined with particular emphasis on the development of the climatic parameters which most influence current runoff patterns.

The means to a solution are complex. The exact physical parameters that determine runoff from a glacierized basin are still insufficiently understood (although a general understanding of the most influential components has been established) and detailed mountain hydrometeorological data are scarce in the Bow Valley. In addition, predicting the effects of climate change on the local meteorology of a given basin is not exact, as GCM predictions are very coarse. A compromise between these two parameters must be reached in order to estimate the effects of climate change on glacier hydrology and mass balance. However, this is not necessarily a problem because a forecasting model consisting of limited inputs can still meet an acceptable level of reliability (Kuhn, 1993).

3. The Study Area

The Upper Bow Valley above Banff encompasses 2226 km^2 and lies on the eastern side of the Great Divide of the Canadian Rocky Mountains. It extends from latitude 51° 30' to 50° 40' North and from longitude 116° 35' to 115° 20' West and has an altitudinal range of approximately 2200 meters, from 1200 m asl to over 3400 m asl (figure 3.1). The topography is rugged and mountainous, with ridges following a general north/south trend, separated by U-shaped valleys that confine the Bow River and its tributaries. The glacierized portion of the basin was estimated at 73km^2 in 1978 (Young, 1995). Most of the glaciers are perched on the western slopes of the valley north of Lake Louise (figure 3.2). Table 3.1 summarizes the land covers of the Upper Bow Valley by sub-basin.

BASIN	Gauge	Area km. sq.	Forest	Glacier	Lake	Rock	% Forest	% Glacier	% Lake	% Rock
Bow River at Banff	BB001	2226.66	1160.06	72.86	15.06	978.68	52.10	3.27	0.68	43.95
Lake Louise	BA001	425.55	174.78	45.13	9.04	196.60	41.07	10.61	2.12	46.20
Pipestone River	BA002	307.79	119.71	9.79	0.35	177.94	38.89	3.18	0.11	57.81
Johnson Creek	BA006	124.17	50.94	0.00	0.31	72.92	41.02	0.00	0.25	58.73
Baker Creek	BA007	125.49	40.34	0.09	0.59	84.47	32.15	0.07	0.47	67.31
Hector Lake	BA008	281.41	83.81	33.20	9.04	155.36	29.78	11.80	3.21	55.21
Forty Mile Creek	BB003	133.41	64.95	0.00	0.13	68.33	48.68	0.00	0.10	51.22
Brewster Creek	BB004	107.15	48.73	0.49	0.25	57.68	45.48	0.46	0.23	53.83
Redearth Creek	BB005	154.16	94.12	1.71	1.23	57.10	61.05	1.11	0.80	37.04
Rest of basin		848.97	566.48	15.65	3.18	263.66	66.73	1.84	0.37	31.06

Table 3.1. Summary of basin land cover for the Upper Bow Valley.

3.1 Climate of the Study Area

The Koeppen climate classification system terms the Canadian Rockies as Dfc, representing a cold, snowy forest climate with no distinct dry season and short, cool summers (Strahler and Strahler, 1989). The hottest month is July, with typical daily maxima reaching 20° to 25°C in the valleys, while the coldest month is January, having an average overnight low of between -15° to -20°C. The Bow Valley above Banff experiences a moist, continental climate with meteorological forcings primarily from the Pacific Ocean and less frequently from the Gulf of Mexico and central Canada. Most of the atmospheric moisture from Pacific storms falls on the ranges west of the Bow Valley. However, typical annual valley floor precipitation is still high, averaging about 450mm a $^{-1}$. Meteorological forcings originating in the prairies occur mostly in early summer and during mid-winter cold snaps, bringing cool, wet conditions which can last for up to a week at a time. A brief summary of climatic data for Banff, Castle Mountain and Lake Louise from 1961-90 is presented in table 3.2.

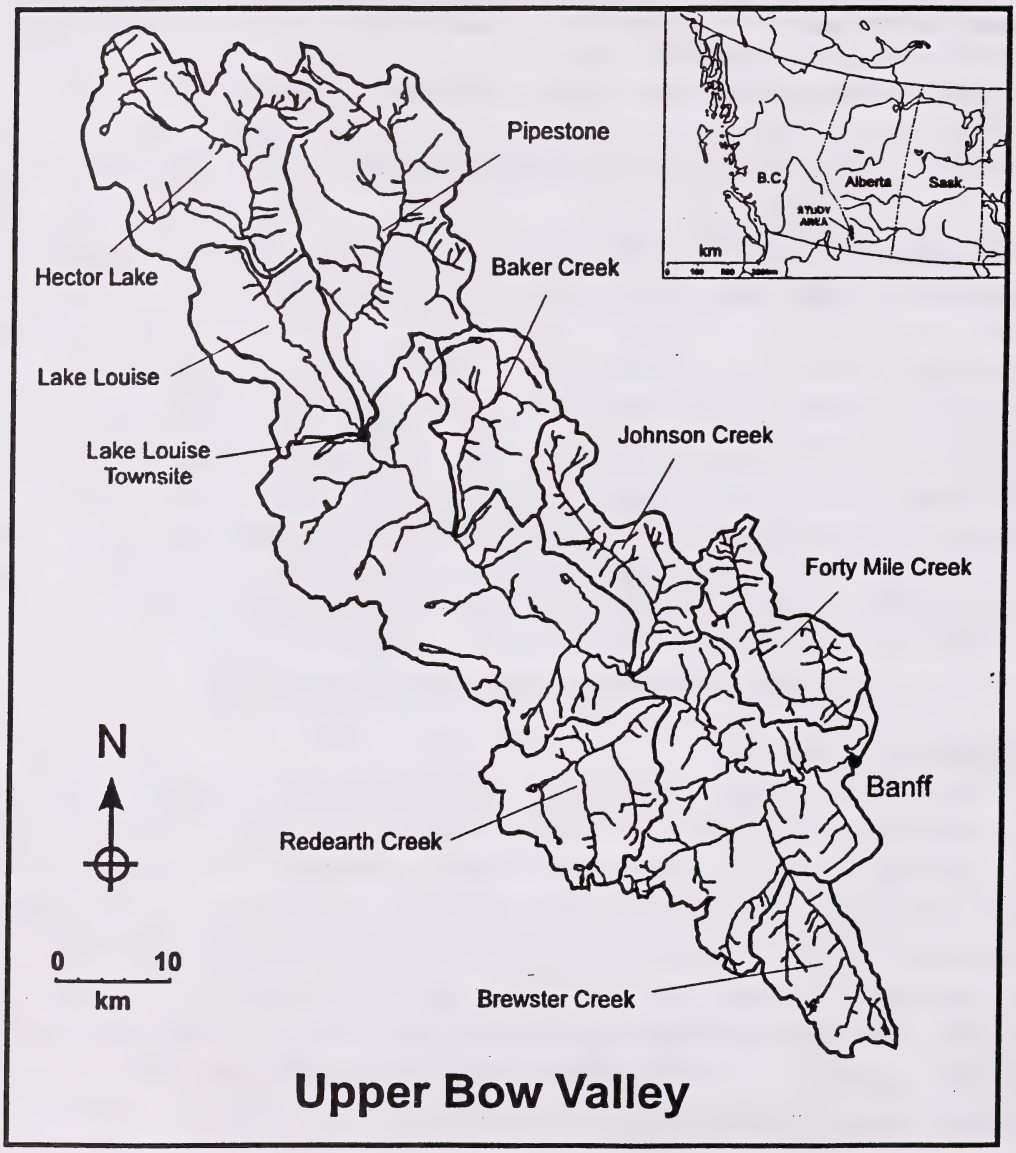


Figure 3.1. The Bow Valley above Banff with sub-basins and rivers delineated.

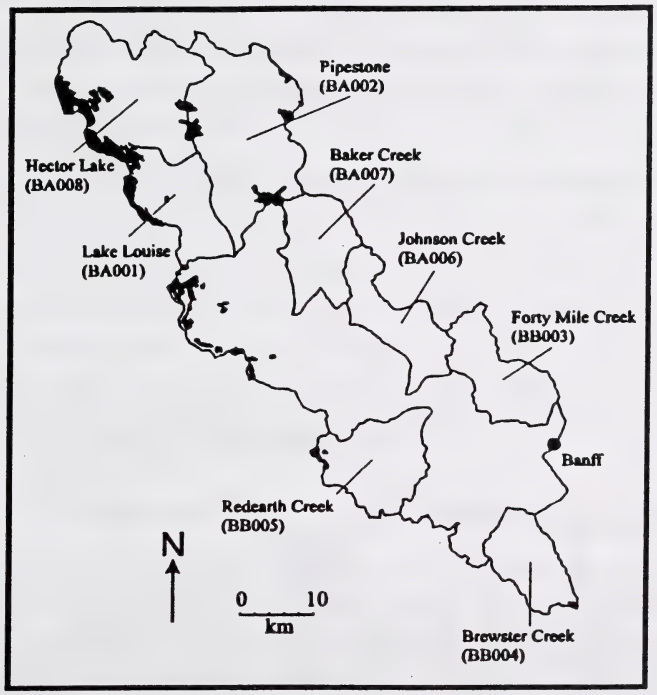


Figure 3.2. Glacier distribution within the Upper Bow Valley (digitized from 1977 NTS maps).

Location	Elev. (m)	Mean temp °C	Days above 0 °C	Daily July High	Daily Jan Low	Annual Ppt (mm)	Annual Snow (cm)	Days with rn/sn
Banff	1397	2.9	158	22.2	-14.9	468	244	78/74
Castle Mt.	1360	3.0	149	22.9	-15.7	866	459	67/67
Lake Louise	1524	-0.4	94	20.4	-21.4	602	329	69/63

Table 3.2. Climatic data for Banff, Lake Louise and Castle Mountain Ranger Station 1960-1991 (Source: Atmospheric Environment Service,1993).

3.2 Banff Meteorological Record

3.2.1. Temperature

Meteorological data for Banff (1887-1991) are presented in figure 3.3. In the Banff temperature record, it is possible to distinguish five distinct periods (table 3.3). The start of the record indicates a period of transition (1887-1903): a gradual warming of temperatures from those typical of the Little Ice Age. It is interesting to note that this period displays very little inter-annual temperature variability typical of transitional periods in climate (Sreenath, 1993). The next period, from about 1904 to 1946, displays warmer temperatures (2.3°C) with a slightly higher variance (0.8). A slight warming trend can be observed over this period. A distinct cooling period exists between 1947 and 1957. Average temperatures for this decade sank to 1.2°C. In addition, inter-annual variability was the greatest in the observed record. By the late 1950's the temperature rose significantly and remained relatively stable until about 1980, when a distinct increase occurred. From 1980 to 1991, the mean temperature was 3.3°C - the warmest in the record.

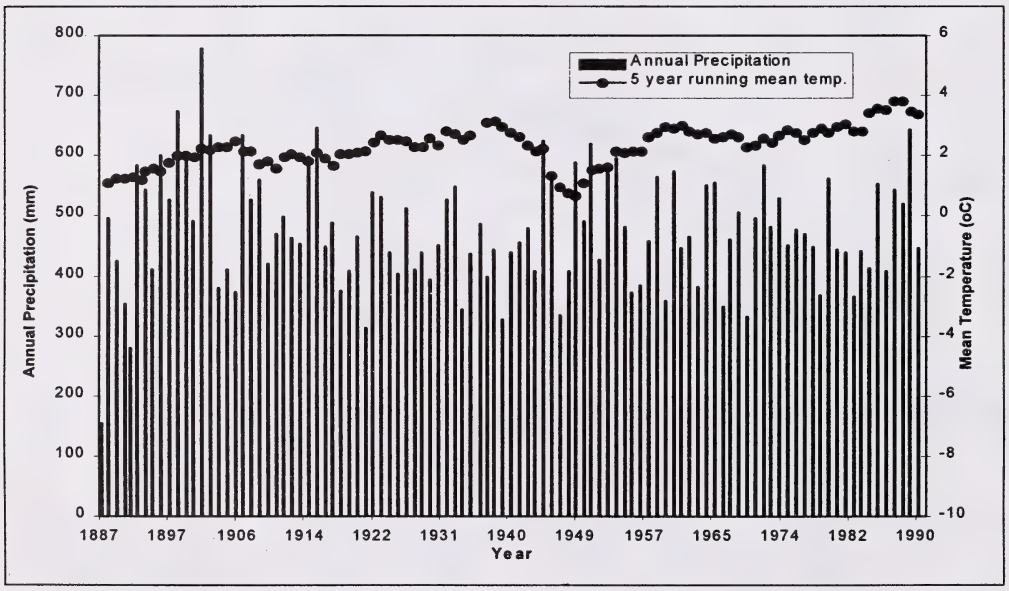


Figure 3.3 Banff annual meteorological data 1887-1991

Years	Mean Temp °C	Variance
1887-1903	1.7	0.3
1904-1946	2.3	0.8
1947-1957	1.2	2.8
1958-1979	2.7	0.4
1980-1991	3.3	0.8

Table 3.3. Statistical trends in the Banff temperature record.

Nicholls et. al. (1996) have addressed the importance of examining the daily temperature range when assessing the observed climate variability. In the Banff record, a gradual increase in both annual maximum (T_{max}) and annual minimum temperature (T_{min}) is evident (figure 3.4). What is interesting to note is that T_{min} displays a greater linear increase than T_{max}. The trendline slope for T_{min} is 0.0014, compared the T_{max} trendline slope of 0.0009 (roughly double). Although this relationship is fairly insignificant, it nonetheless substantiates the findings of Karl et al. (1993), which suggest that, worldwide, minimum land-surface air temperatures have been increasing more than maximum land-surface air temperatures. This increase is mostly due to a faster rise in night temperatures, as dew-point temperatures are more sensitive to longwave radiation fluxes.

3.2.2. Precipitation

The most noticeable characteristic of the precipitation record (figure 3.3) is that it is highly variable. The inter-annual noise associated with the precipitation regime of the Upper Bow Valley makes it difficult to discern decadal or inter-decadal trends. Banff receives an average 450 mm per annum, although inter-annual variability can be up to 60%. Gadd (1995) has suggested that years of El Niño Southern Oscillation display a marked decrease in annual precipitation in the Upper Bow Valley. Major El Niños occurred in 1925-6, 1939-41, 1957-8, 1972-3 and 1982-3 (Barry and Chorley, 1987). Although it is difficult to separate El Niño influence from the inter-annual noise, most of these years are associated with typically lower annual precipitation.

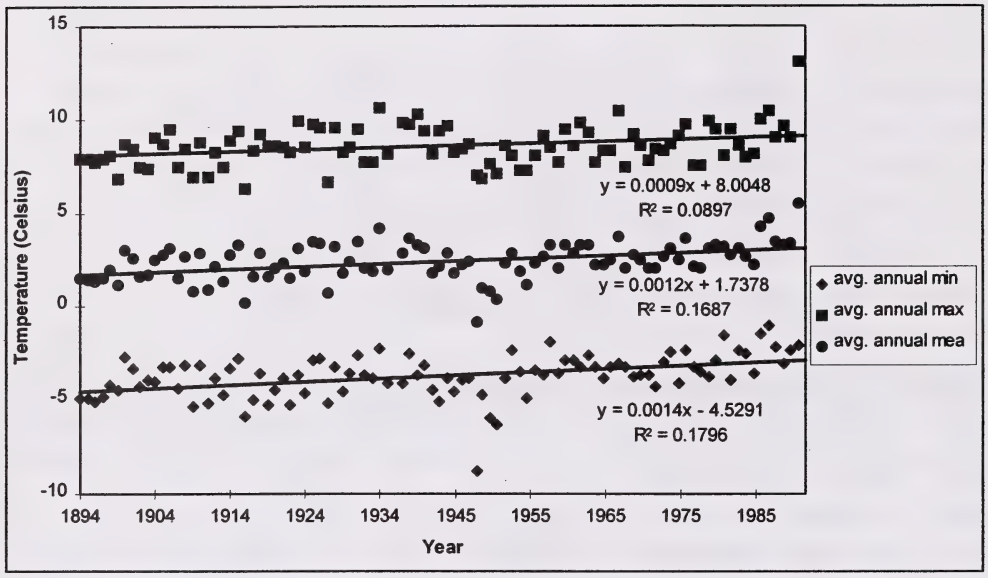


Figure 3.4 Annual Banff maximum, minimum and mean temperatures for 1894-1991

3.3. Bow River above Banff Discharge Record

The discharge record of the Bow River at Banff extends back to 1911 (figure 3.5). Discharge patterns observed at the Bow River at Banff display high inter-annual variability (table 3.4). The record suggests no obvious trends in the 82 year period. There was an interval of generally low flows from the late 1930's to about 1950, and again from 1970 to 1991, whereas the 1960's experienced higher than average discharge. Variability of discharge has been increasing. The variance for years between 1910 and 1991 is 28.02 $m^3 \times 10^6$. For years between 1910 and 1970, the variance stays beneath the record average, however, between 1970 and 1991, the variance jumps to 33.44 $m^3 \times 10^6$. This may be a result of increased glacial melt contribution and / or changing snowmelt patterns caused by climatic changes, specifically the higher temperatures seen during this period (table 3.3). Increased variability in discharge will create difficulties for management of the resource by decreasing the stable supply.

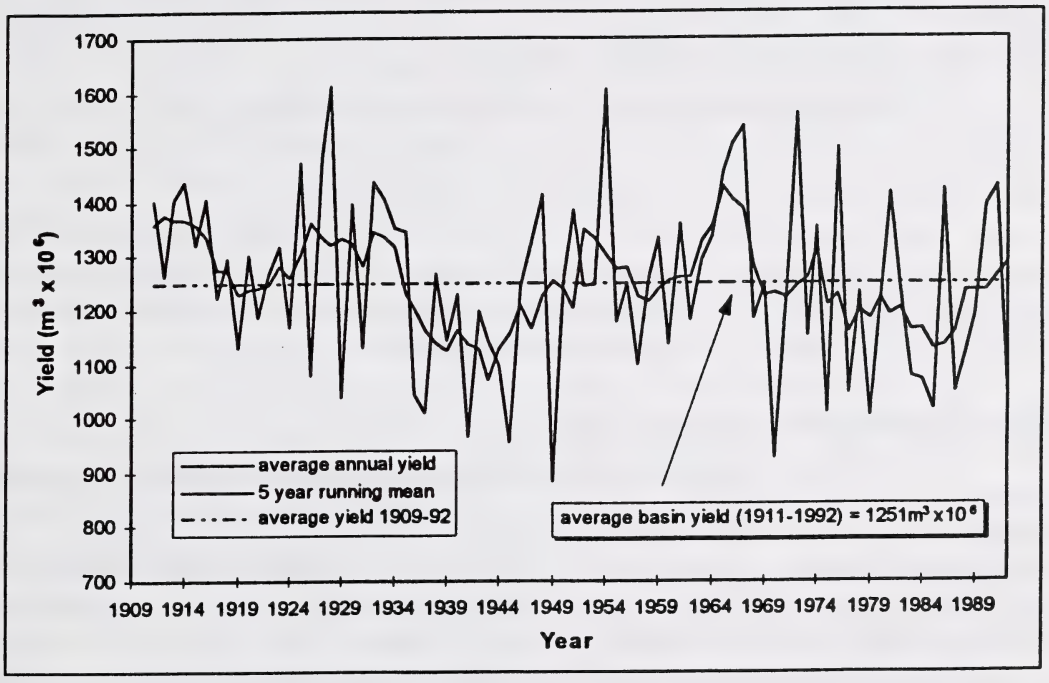


Figure 3.5. Bow River Hydrograph at Banff 1911 -1992.

Years	Mean Q in $m^3 \times 10^6$	Variance
1911-1991	1251	28.02
1911-1936	1305	21.98
1937-1954	1201	26.24
1954-1969	1291	22.77
1970-1991	1204	33.44

Table 3.4. Mean annual discharge and variance figures for Bow River at Banff discharge.

4. The UBC Model

4.1. Model Selection and Description

The objectives of this project ideally require a fully-distributed, physical model. Unfortunately, the Bow Valley data set contains only simple meteorological variables: daily maximum and minimum temperature, daily precipitation and periodic snowcourse data, which limit the model criteria to an empirical or conceptual model with limited data requirements.

The UBC Model (Quick and Pipes, 1994), designed specifically to provide a computational representation of mountain watershed behaviour, satisfies the data constraints. It is a quasi-physical, coarsely distributed model designed primarily for short term hydrograph forecasting. However, because the model can operate continuously using successive meteorological data, it is feasible to use the model for long term forecasting. The model compared well with other watershed models in the World Meteorological Organization's Intercomparison of Models of Snowmelt Runoff (WMO,1986) and is used extensively by B.C. Hydro for operational flow forecasting of the Williston and Columbia watersheds. Thus, the UBC Model was selected for the project.

4.2. Data Requirements and Design Constraints

The model requires a minimum of input data, which includes daily minimum and maximum temperature and daily precipitation. From these data both the timing and quantity of streamflow resulting from snowmelt, icemelt, rainfall and groundwater is calculated. As a consequence of the minimal data requirements, the model inherently makes gross assumptions when computing output. The model interprets meteorological point data and extrapolates values for the entire watershed based on the operator's physical description of the basin.

In order to calibrate the model, high quality streamflow reference data are needed. It is desirable to use flow data from a meteorologically diverse number of years. This will sensitize the model to basin response for a variety of meteorological conditions. However, using an hydrologically extreme, anomalous, year to calibrate the model can muddle the forecast efficiency. This is because the model may process average storm events with an extreme event bias.

The estimation of snow packs by the model is accomplished by using two data sources: daily precipitation from meteorological stations and snow course measurements. Snow course measurements are not used as direct input, but rather as a reference to compare estimated snow accumulation. Daily precipitation values from meteorological stations are input directly into the model to estimate snow accumulation per elevation band.

5. Calibration of the UBC Model to the Upper Bow Valley

5.1. Spatial Resolution of the Calibration

Ideally, calibrating the model to each sub-basin in the Upper Bow Valley would lead to a better understanding of the seasonal discharge variation of the basin. However, it is problematic to assume that the Lake Louise and Banff meteorological data would be representative of the smaller basins located around the periphery of the Upper Bow Valley. In addition, it is assumed that the basin-wide hydrologic signature overrides the sub-basin idiosyncrasies. Thus, the entire basin was calibrated as a single hydrologic unit.

5.2. Calibration Approach

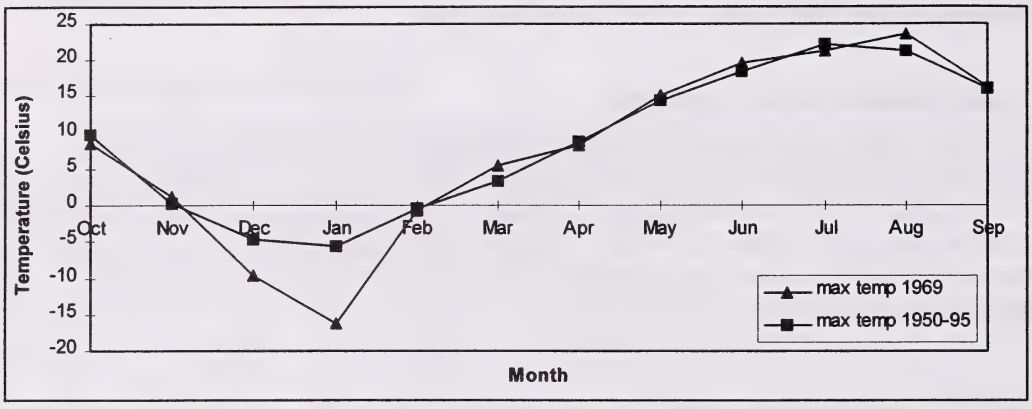
Model calibrations were performed for years 1950-1990, however the calibration process described below was specifically optimized for hydrologic year 1969. It was found that 1969 displayed the most accurate calibration results (although several other years were also highly efficient) and was a typical climatic year (figure 5.1), enabling it to be used for the climatic sensitivity analysis. In addition, a great amount of hydrological data were collected during this period at the Peyto Glacier Basin as part of the reseaech initiatives of the International Hydrological Decade. This allows for critical examination of model performances in comparison to the collected data.

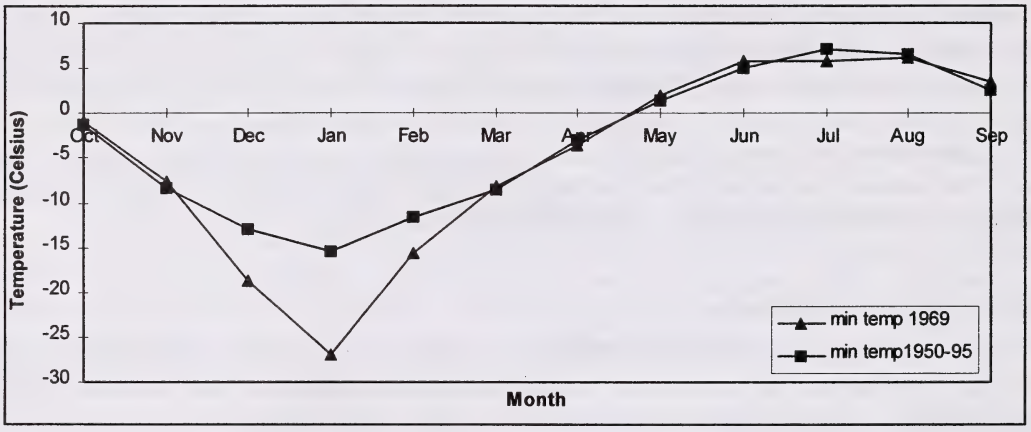
5.3. Estimating Glacier Recession

To extend the record of glacier recession in the Upper Bow Valley back through time from 1966, the work of Hopkinson (1997) was used. Detailed photogrammetric analysis was conducted by Hopkinson (1997) on the glacier extents in 1951 and 1993 in the Hector Lake Basin. The annula recession values from 1951 to 1993 based on the modelled (1951-1966) and observed (1967-1993) Peyto Glacier mass balance record were then estimated. The rates of areal glacier recession per elevation band in the Hector Basin (as estimated by Hopkinson) were extrapolated to the entire Bow Valley above Banff. An hypsographic bar graph summarizing assumed glacier retreat between 1951 and 1993 is presented in figure 5.2.

5.4. Hypsographic Data

In order to produce a watershed description file for the Upper Bow Valley, hypsographic data (digitized from 1978 NTS maps) from the Bow Valley Study (Young, 1995) were used. These data are presented in figure 5.3.





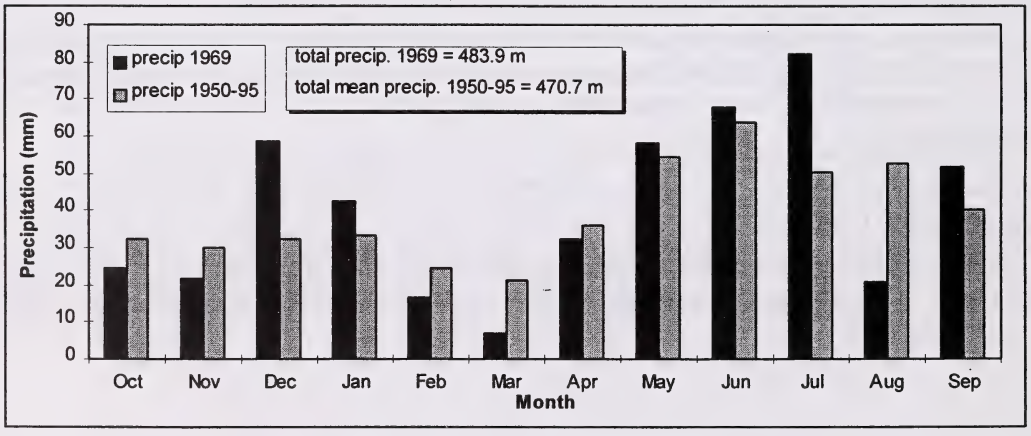


Figure 5.1 Comparison of the mean 1950-95 precipitation and maximum and minimum temperature with observed values for the hydrologic year 1969

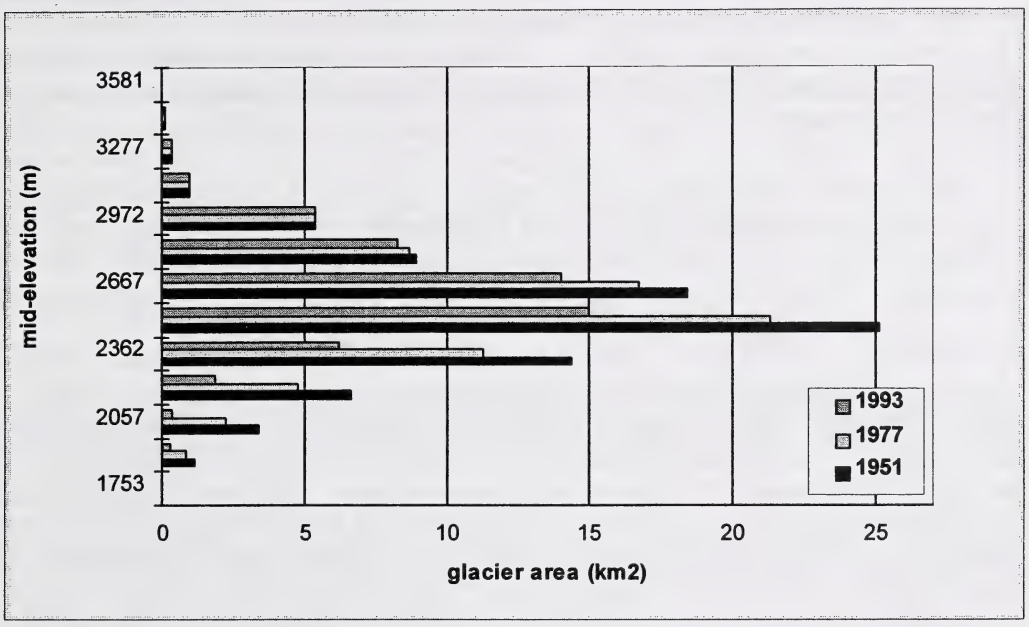


Figure 5.2. Hypsographic curve of estimated glacier areas in the Upper Bow Valley.

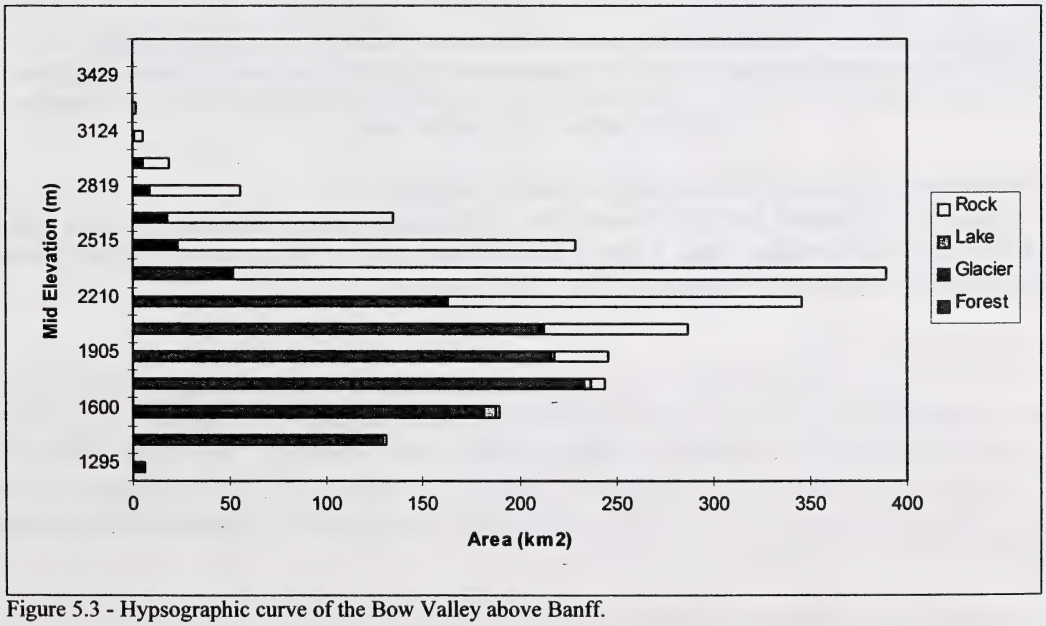


Figure 5.3 - Hypsographic curve of the Bow Valley above Banff.

5.5. Elevation Bands and Land Cover Description

Within the calibration file, the Upper Bow Valley was separated into nine elevation bands. The UBC Model allows for the description of various components within each elevation band. The values for these parameters are presented in table 5.1. Values for the mean area (C0ALEM), forested fraction (C0TREE), and the glaciated area (C0AGLA) of each elevation band were determined directly from the hypsographic curve data.

	Elevation Band								
Parameter	1	2	3	4	5	6	7	8	9
C0ELEM (m)	1371	1676	1905	2133	2362	2590	2895	3200	3505
C0ALEM (km^2)	137.14	433.35	246.32	631.85	389.54	363.54	74.57	6.92	0.51
C0TREE (%)	0.985	0.958	0.875	0.581	0.102	0.008	0	0	0
C0CANY (%)	80	80	80	70	60	50	0	0	0
C0RIEN	0.2	0.2	0.5	0.5	0.5	0.5	0.7	0.7	0.7
C0AGLA (km^2)	0	0.01	0.83	7.05	11.32	38.05	14.08	1.29	.1
C0AGOR (%)	0	0	100	100	100	100	100	100	100
C0IMPA (%)	0	.05	.15	.2	.3	.7	.72	.735	.743

Table 5.1. Summary of Upper Bow Valley watershed description (C0ELEM = mid elevation of band; C0ALEM = Mean area of the band; C0TREE = forested fraction; C0CANY = density of the forest canopy; C0RIEN = orientation index; C0AGLA = glacier area; C0AGOR = fraction of glaciated area with south orientation; C0IMPA = fraction of impermeable area).

5.6. Precipitation Modelling - Meteorological Station Selection

Optimum efficiencies for UBC Model flow estimations were obtained when using Banff precipitation data for elevation bands 1 and 2 (elevations 1219 - 1790 m asl) and Lake Louise precipitation data for bands 3 - 9 (elevation 1790 - 3657 m asl).

5.6.1. Form of Precipitation

The model must distinguish between precipitation as either snow or rain in each elevation band. This is computed using the model parameter A0FORM, which was kept at the default value of 2°C. Thus, when the mean daily temperature in a given elevation band is over 2°C, then all precipitation is rain. If the mean daily temperature is between 0°C and 2°C, a proportion of the precipitation will be specified as rain. This proportion is dependent on the mean daily temperature. All precipitation falling at temperatures below 0°C is considered snow.

5.6.2. Orographic Enhancement of Precipitation

An orographic enhancement factor (P0GRADL) of 10% per 100m was used for elevations up to 2200 masl (E0LMID). This precipitation gradient was lowered to 3% per 100m (P0GRAM) for

elevations over 2200 masl (E0LHI). A schematic of precipitation modelling for the Bow Valley above Banff is presented in figure 5.4.

5.6.2.1. Rationale and Confidence

Values for the modeling of orographic precipitation enhancement were estimated by examining the altitudinal variation of snow course data (figure 5.5). Rainfall data over a significant altitudinal range do not exist in the Upper Bow Valley, and therefore snow course data had to be used to estimate the orographic enhancement of precipitation. Records for Bow River, Bow Summit, Chateau Lawn, Mirror Lake, Ptarmigan Hut, Upper Pipestone and Sunshine snow courses were examined. Average snow course data from these stations between 1967 and 1994 reveal a vertical gradient in mean snow water equivalence of about 11.25% per 100m (figure 5.5).

5.6.3. Estimating Snowpacks

The model contains a snow precipitation representation factor (P0SREP) that allows the modification of point source snow precipitation data to become more representative of basin wide conditions. It was found that both Banff and Lake Louise snow precipitation data performed best when assigned a P0SREP value of 0.1, which essentially increases precipitation by 10%. This value was determined through examination of the regional snow course data set and from the model calibration statistics and is depicted in figure 5.4.

5.6.4. Estimating Rainfall

Rainfall is estimated using the same algorithms as snowfall. However this requires that a separate precipitation representation factor is used for rain. A liquid precipitation representation factor (P0RREP) of 0.1 proved most effective for both Banff and Lake Louise meteorological station data. This value for P0RREP was determined by examining late spring and summer Bow at Banff discharge and rainfall data, and by conducting a sensitivity analysis for a range of P0RREP values.

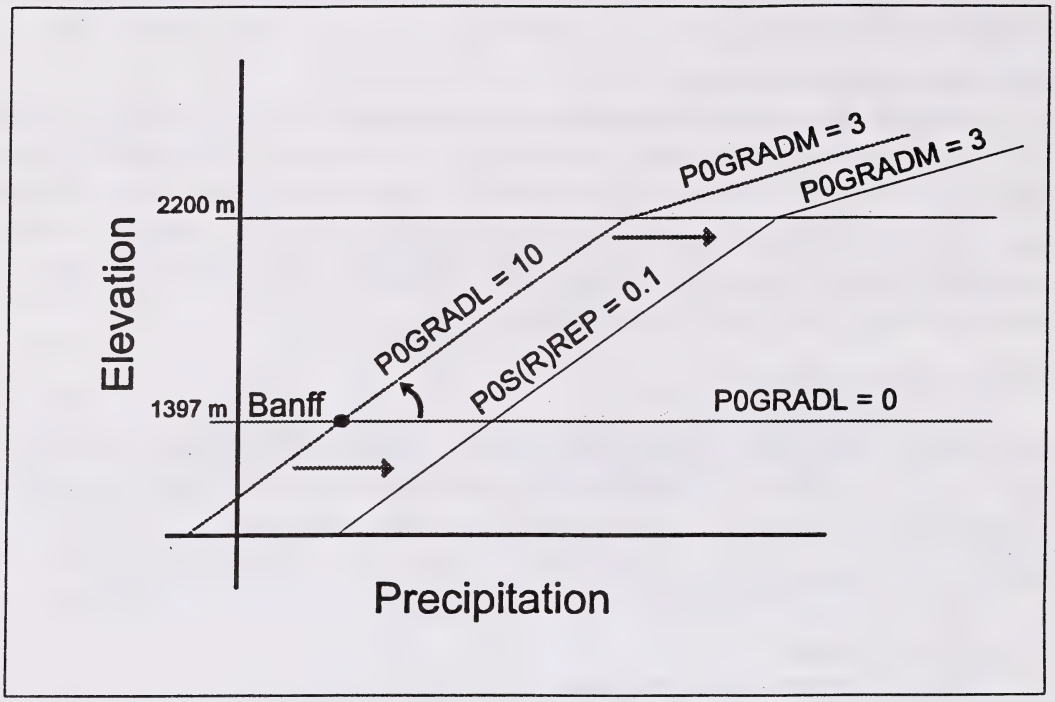


Figure 5.4. Schematic of precipitation modelling (where PROGRADL is the orographic enhancement factor; POGRADM is the precipitation gradient; POSREP is the snow precipitation representation factor and PORREP is the rain precipitation representation factor).

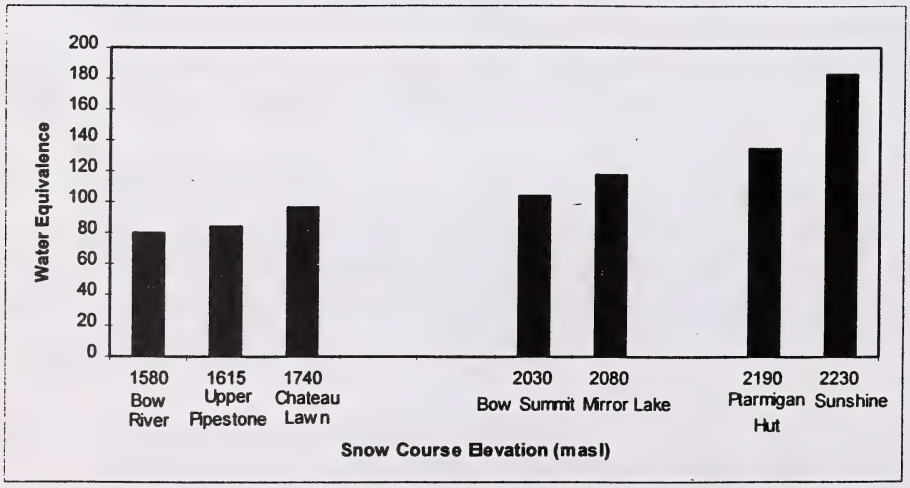


Figure 5.5. Average 1967-1994 water equivalence (mm) and elevation for Upper Bow Valley snow courses.

5.7. Temperature Lapse Rates

The lapse rates for temperature were calculated using the default settings of the model, and are summarized in table 5.2. The threshold amount of precipitation for the moist temperature lapse rate (A0PPTP) was held at the model default of 6 mm.

Model Parameter	Temperature Lapse Rate Conditions	Temperature Lapse Rate (°C/1000m)
A0TLZZ	moist adiabatic lapse rate	6.4
A0TLZP	lapse rate when ppt > A0PPTP	6.4
A0TLXM	lapse rate of Tmax when elevation of meteorological station < 2000m	10
A0TLNM	lapse rate of Tmin when elevation of meteorological station < 2000m	0.5

Table 5.2. Default lapse rates used in the calibration of the UBC Model to the Upper Bow Valley.

5.8. Snow and Ice Melt Calculation

The default snowmelt algorithms in the model were not adjusted. However, the albedo of ice was lowered from 0.3 to 0.23 for a more reasonable representation of the albedo of glacier ice.

5.9. Evapotranspiration, Wind and Cloud Cover Modelling

Evapotranspiration, wind and cloud cover for the basin are calculated using the default settings suggested in the model.

5.10. Groundwater Estimation and Routing

Groundwater percolation (P0PERC) was assigned a value of 40mm/day. Of this, 35.5% was routed to the deep zone share (P0DZSH). Upper groundwater (P0UGTK) was given a flow time constant of 30 days, while the time constant for deep groundwater (P0DZTK) was assigned a value of 140 days. The release times are routed through a single linear reservoir assumed as default by the model. These figures were derived entirely from the optimization routine within the model as there were no calibration data available for the study area.

6. Results for the 1969 Calibration

6.1. Explanation of Statistical Algorithms

Two statistical algorithms are used to compare model output with observed flows: the coefficient of efficiency and the coefficient of determination. The coefficient of efficiency (e!) compares the timing and volume of the estimated with the observed hydrograph, and is calculated as follows:

$$e! = 1 - \frac{\sum_{i=1}^{n} (Qobs_i - Qest_i)^2}{\sum_{i=1}^{n} (Qest_i - \overline{Qobs})^2} \tag{6.1}$$

where $$\overline{Qobs} = \frac{1}{n} \sum_{i=1}^{n} Qobs \tag{6.2}$$

the number of days for daily runs or hours for hourly runs
the observed flow on day/hour i
$Qest_i$ = the calculated flow on day/hour i

An efficiency of 1 translates to a perfect estimation. Values deviating from 1 indicate problems associated with volume and/or timing. This statistic is more sensitive to exaggerated peaks than to small underlying flows.

The coefficient of determination (r^2) is a function that describes how well the shape (timing) of the calculated hydrograph corresponds to the shape of the observed hydrograph - it is independent of volume representation. The coefficient of determination is calculated as follows:

$$r^2 = 1 - \frac{\sum_{i=1}^{n} (Qobs_i - (b.Qest_i + a))^2}{\sum_{i=1}^{n} (Qobs_i - \overline{Qobs})^2} \tag{6.3}$$

where

$$a = \frac{1}{n} \sum_{i=1}^{n} Qobs_i - b \sum_{i=1}^{n} Qest_i \tag{6.4}$$

and

$$b = \frac{\sum_{i=1}^{n} (Qobs_i)(Qest_i) - \frac{1}{n} \sum_{i=1}^{n} Qest_i \sum_{i=1}^{n} Obs_i}{\sum_{i=1}^{n} (Qest_i)^2 - \frac{1}{n} \sum_{i=1}^{n} Qest_i} \tag{6.5}$$

6.2. Results of the 1969 Upper Bow Valley Calibration

The statistical calibration results for hydrologic year 1969 are presented in table 6.1 and the observed and calculated hydrographs are displayed in figure 6.1. Overall, the calibration results for hydrologic year 1969 are very good (meteorological data presented in appendix 7). In all, 99% of the total yield was estimated. The coefficient of efficiency (e!) for the year is 0.926, and coefficient of determination (r^2) is 0.933. These values do not drop considerably for the April-September period when the basin is most hydrologically active. The winter efficiency (0.75) is deceiving as the statistic is based on relative values; visual analysis of the hydrograph confirms that winter base flow errors are minimal. As the coefficient of determination indicates in figure 6.2, the overall shape of the calculated hydrograph is accurate, suggesting that the model performs well in representing the general hydrologic trends of the basin.

Period (1968-69)	Observed *Avg. Daily Q (cumecs)*	Estimated *Avg. Daily Q (cumecs)*	Observed Yield ($m^3 \times 10^6$)	Estimated Yield ($m^3 \times 10^6$)	Coefficient of Efficiency	Coefficient of Determination
Oct 1 - Sept 31	39.8	40.1	1254.96	1266.85	0.926	0.933
Apr 1 - Sept 31	67.1	66.8	1060.62	1052.68	0.872	0.893
Oct 1 - Mar 31	12.3	13.5	194.34	214.17	0.7504	0.903

Table 6.1. Statistical results for the calibration file applied to hydrologic year 1969.

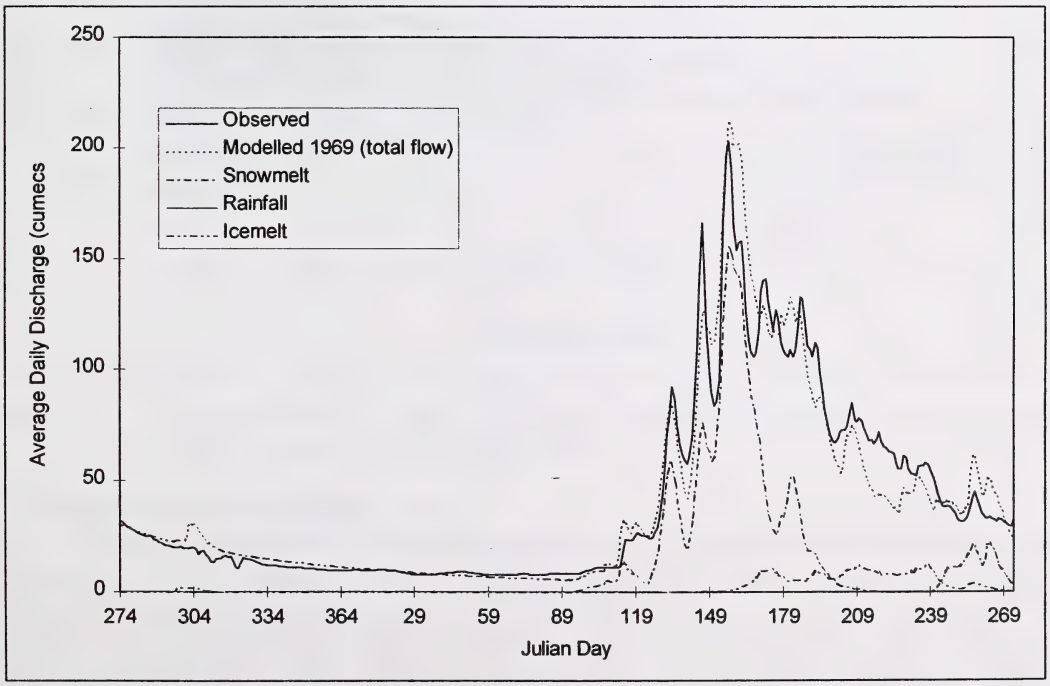


Figure 6.1. Observed and modelled hydrograph for hydrologic year 1969.

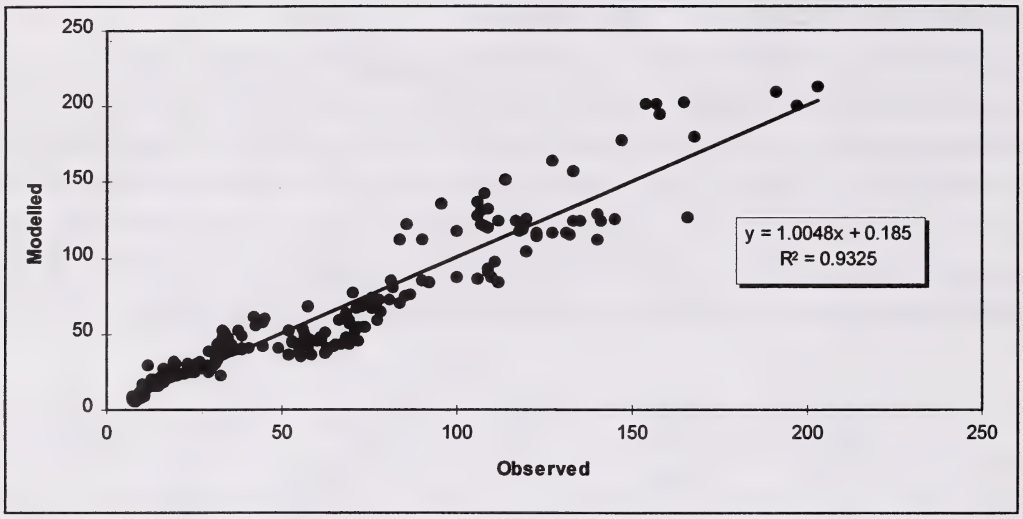


Figure 6.2. Scatterplot between observed and modelled average daily discharges for Bow River at Banff for year 1969.

7. Application of Climatic Scenarios and Glacier Recession to the Upper Bow Valley Model Calibration File

7.1. Glacier Area Change

In order to estimate the effect of a changing climate on the hydrology of a watershed, the dynamic characteristics of all land covers must be estimated. It is assumed that rock and forest covers in the Upper Bow Valley will remain constant. To account for glacier melt, a linear rate of areal ice recession per elevation band as observed from 1951-1993 was assumed (based on photogrammetric measurements from the Hector Basin by Hopkinson, 1997) (figure 7.1). The observed trend was extended forward to estimate a 30% (modest glacier change) and a 62% (extreme glacier change) recession of the estimated 1993 areal glacier extent for the entire Bow Valley above Banff. These values were entered into the Bow Valley watershed description files of the UBC Model. In addition, a file was created assuming no glacier coverage.

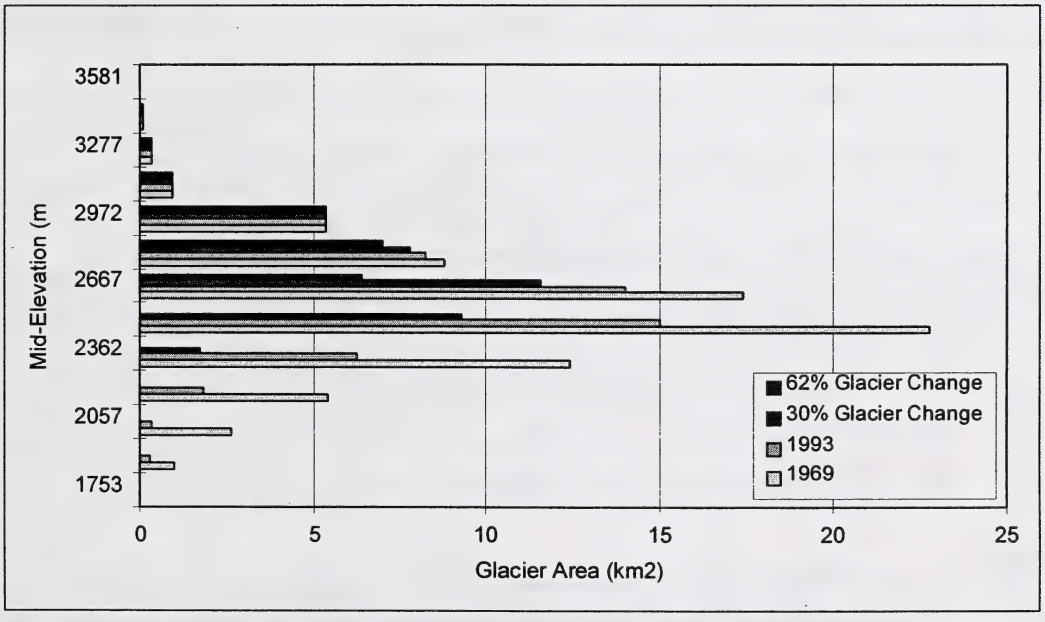


Figure 7.1 Hypsographic curve of estimated future glacier area extents based on the observed 1951-1993 linear trend. Percentage change from 1993 estimated values.

7.2. Hypothetical Climatic Scenarios

Climatic scenarios were formulated based on $2xCO_2$ predictions from 8 General Circulation Models or GCM's (Canadian Centre for Climate {CCC}, Victoria; Commonwealth Scientific and Industrial Research Organization {CSIRO}, Melbourne; Geophysical Fluid Dynamics Laboratory {GFDL}, Princeton; Max Planck Institute for Meteorology {MPI}, Hamburg; Meteorological Research Institute {MRI}, Tsukuba, Japan; National Centre for Atmospheric Research {NCAR}, Boulder; and the United Kingdom Meteorological Office {UKMO}, Bracknell). With reference to the study area, there is agreement between most of these GCM's that winter temperatures will experience greater increases in comparison to summer temperatures. In addition, all models suggest that minimum daily temperatures

will be most sensitive to these increases resulting in a decrease of the diurnal temperature range. It is also estimated that winter precipitation will increase as a result of a pronounced maritime influence in western Canada. Summer precipitation is not expected to vary considerably. The Intergovernmental Panel on Climate Change (Gates, et. al., 1996) provides a summary of these model predictions.

Although there is general agreement in predicted climatic trends for most models, absolute values display significant variability between GCM's. To represent the broad range of predictions of these models, several climatic scenarios were drafted (table 7.1). The minimum temperatures were given preferential weighting in all scenarios to simulate the estimated decrease in the diurnal temperature range. Winter precipitation was also preferentially weighted over summer precipitation; a 0.5 mm/day increase in winter precipitation is approximately equivalent to a 50% increase in the observed 1969 record and a 0.1 mm/day increase is about 10%. The winter period is defined as October to April. Summer is defined as May to September (based on typical hydrometeorological conditions).

The meteorologic file for hydrologic year 1969 (from October 1 1968 to September 31 1969) of the UBC Model was adjusted to simulate each scenario. Model runs were performed using all four scenarios in turn as the meteorologic forcing of the watershed description files of calculated 1969 and adjusted glacier extents (30% and 62% reduction and no glaciers).

Scenario	Temperature (°C)				Precipitation (mm/day)	
	Winter		Summer		Winter	Summer
	max	min	max	min		
1	1.5	3	1	2	0.5	0.2
2	0.5	1	0.3	0.6	0.1	0
3	1.5	3	1	2	0	0
4	0	0	0	0	0.5	0

Table 7.1. Climatic scenarios (all values indicate increases in precipitation or temperature).

7.3. Results

Presenting the results of all four climatic scenarios vs. the 5 watershed files (original 1969, 1993, 30% and 62% reduction in glacier area and no glaciers) would be redundant as the results overlap in many cases. Adjusting the glacier area does not alter the UBC Model calculations for rainfall, snowmelt, evapotranspiration, and groundwater. Only icemelt is affected. This is because the icemelt routine works independently of all other sub-models.

Thus, in the interest of clarity, results are presented in three parts. The first part presents the UBC Model estimations of Bow River at Banff discharge assuming various degrees of glacier recession. The second part strictly examines the icemelt component of the hydrograph when the climatic scenarios force the model. And finally, the third section deals with the climatic sensitivity of the entire basin; results of the climate scenarios on the original 1969 calibration files are presented in full (all components of the hydrograph including evapotranspiration are examined).

7.3.1. Reduction of Glacier Area Using Observed Meteorological Conditions

UBC Model predictions for watershed files programmed to simulate a reduction in glacier area are presented graphically in figure 7.2 and in tabular form in table 7.2. The UBC Model translates reduction in glacier extents to significant reductions in annual discharge. Naturally, the majority of the discharge attenuation occurred during the summer months: July and August yield was reduced by 21.9% assuming no glaciers. Discharge is lowered most during the initial stages of melt, as glaciers retreat to higher elevations. The model does not calculate any significant variance in the timing between the discharge resulting from glacier area adjustment and the modelled 1969 discharge.

Glacier Area	Reduction in 1969 Annual Yield x 10^6 m^3	% Reduction in 1969 Annual Yield	Reduction in July-August Yield x 10^6 m3	% Reduction in July-August Yield
1993 extent	33	2.6%	22	6.5%
30% reduction	60	4.7%	40	13.1%
62% reduction	85	6.7%	58	17.2%
no glaciers	104	8.2%	74	21.9%

Table 7.2. Reduction of Bow River at Banff discharge resulting from glacier area adjustment.

7.3.2. Reduction of Glacier Area Using Climatic Scenarios

The following results were generated by forcing the UBC Model with the climatic scenarios using watershed files that had been adjusted to account for glacier recession. Only the icemelt component is examined. The results are presented in figures 7.3 to 7.6; total yields are displayed in table 7.3.

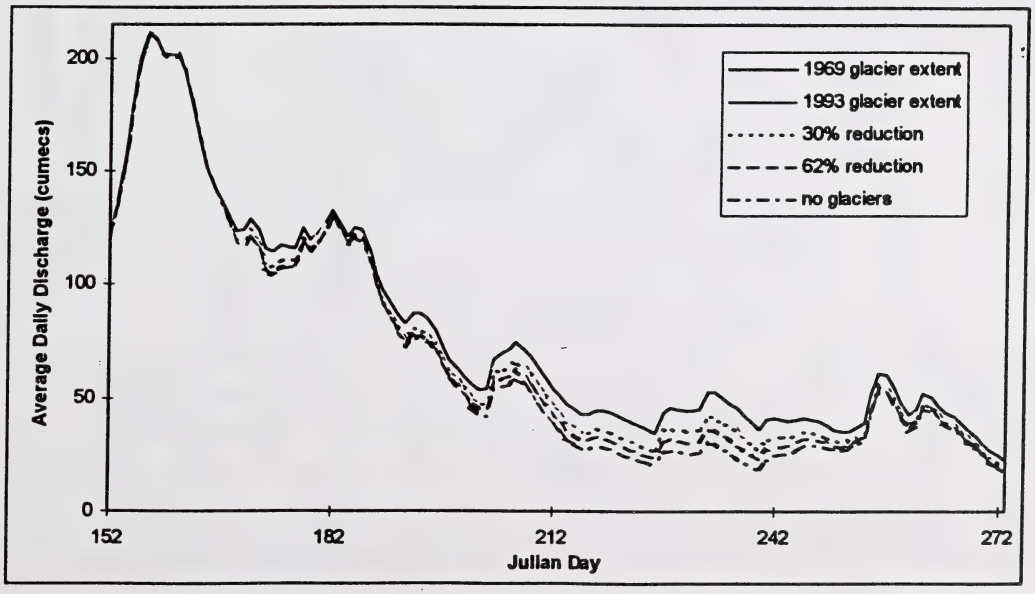


Figure 7.2. Graph displaying the calculated average daily discharge at the Bow River at Banff resulting from the adjustment of glacier area. Percentages indicate the estimated reduction in glacier area from estimated 1993 values.

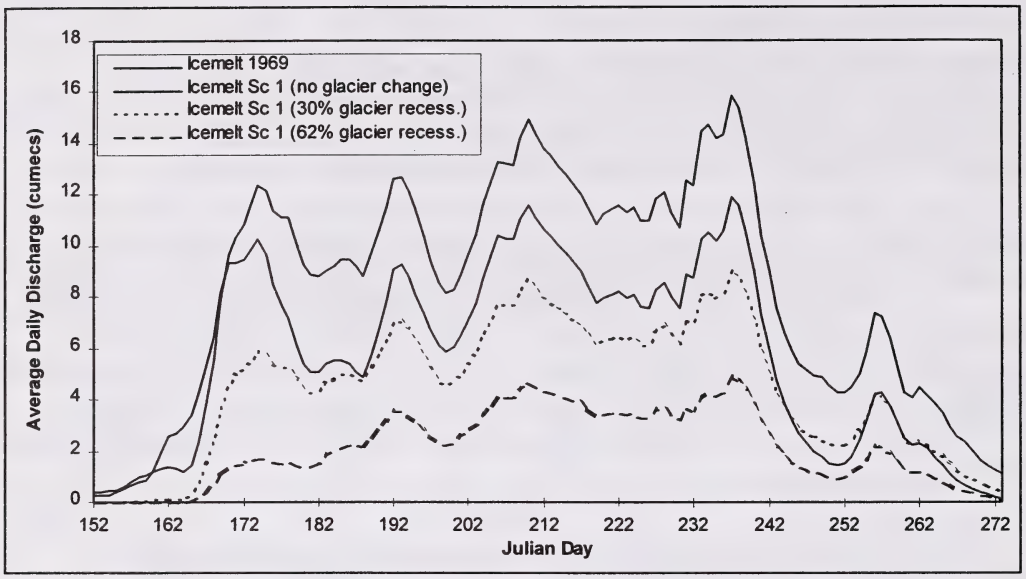


Figure 7.3. Comparison of the UBC Model estimates of icemelt for various glacier extents using climate scenario 1.

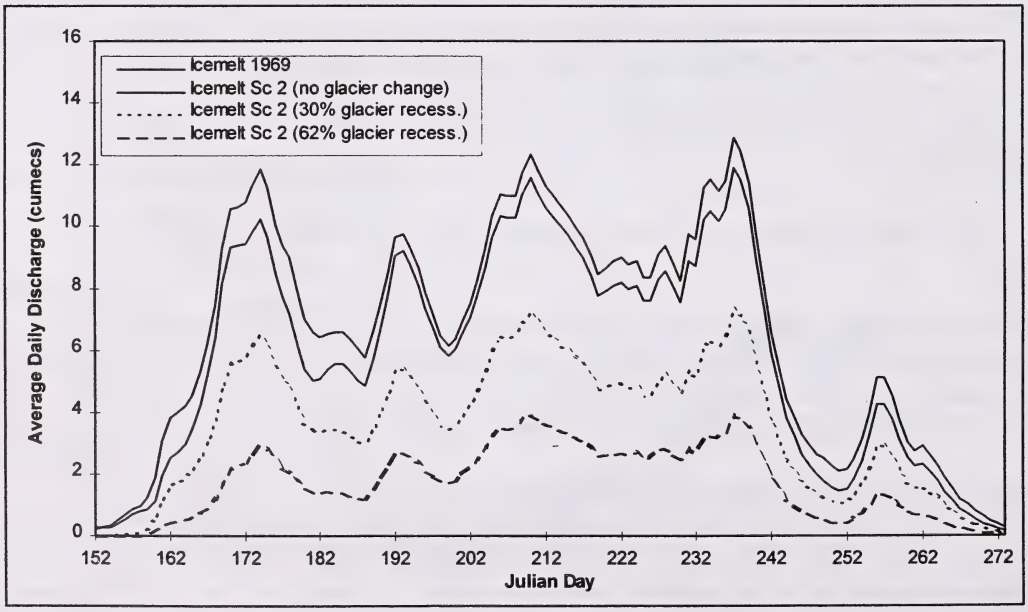


Figure 7.4. Comparison of the UBC Model estimates of icemelt for various glacier extents using climate scenario 2.

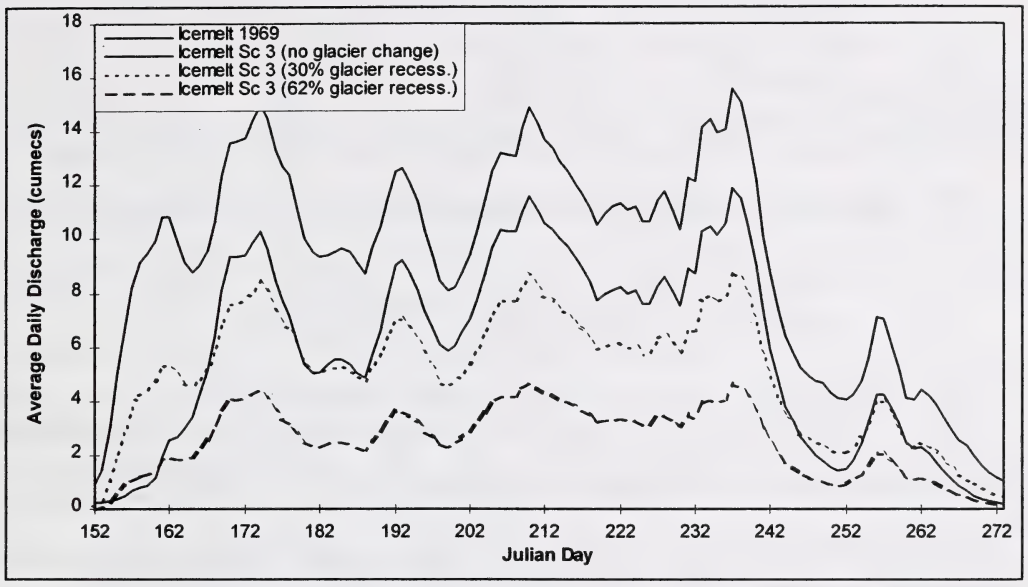


Figure 7.5. Comparison of the UBC Model estimates of icemelt for various glacier extents using climate scenario 3.

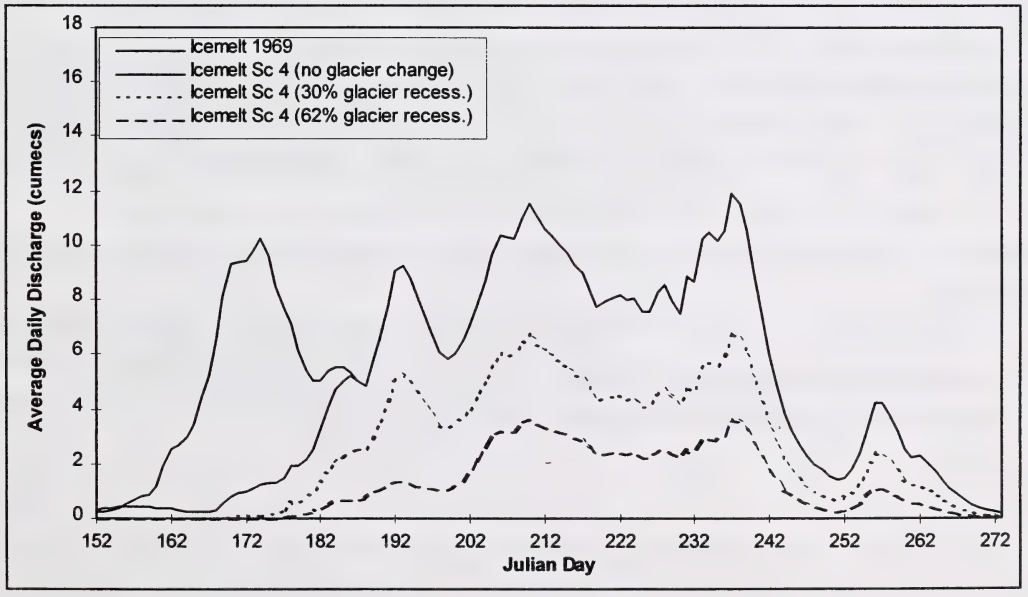


Figure 7.6. Comparison of the UBC Model estimates of icemelt for various glacier extents using climate scenario 4.

	Climate Scenario			
Watershed File	1	2	3	4
1969 calibration	87.7	69.9	98.7	51.2
30% glacier reduction	46.8	37.9	53.6	27.5
62% glacier reduction	22.7	18.5	26.9	12.9
1969 calibration file forced by observed meteorological file produced 61.755 m^3x10^6 of icemelt				

Table 7.3. Total yields of icemelt production in $m^3 \times 10^6$.
Percentages of glacier reduction indicate recession from 1993 values.

A theme evident in all scenarios is that the model predicts glaciers to be less sensitive hydrologically to the heat budget as they decrease in size. Discharge peaks present in the 1969 calibration are progressively smoothed out as glacier area decreases. This is most likely the result of adiabatic temperature lapse rates causing cooler temperatures in the higher altitudes and thus dampening icemelt production.

A 50% increase in snowpack water equivalence delays icemelt. This trend is accentuated as glaciers ablate to higher elevations (figure 7.6). Using climate scenario 4, icemelt is delayed by about 2 weeks assuming no changes in glacier area, whereas in the case of a 62% ice loss, melt is delayed by almost a month. Increased temperatures combat the effects of a deeper snow pack (figure 7.3), which results in an icemelt delay of about a week for each watershed file. Increased snowmelt will also contribute to groundwater recharge.

Increased temperatures accentuate and prolong icemelt. UBC Model discharge predictions for a 30% and 62% reduction in glacier size approach, and in some areas exceed, the original 1969 calibration flows (figure 7.5). When assuming a 30% ice loss, the model predicts that a significant increase in temperature alone, as in climate scenario 3, can generate high yields of icemelt; 54 $m^3 \times 10^6$ as compared to the original 1969 calibration file which produced 62 $m^3 \times 10^6$.

7.3.3. Application of Climatic Scenarios to the 1969 Upper Bow Valley Watershed File (no adjustment to glacier area)

A summary of the UBC Watershed Model estimates of icemelt, snowmelt, rainfall, groundwater and evapotranspiration for the 1969 watershed file when forced by all four climatic scenarios is presented in table 7.4. Bolded figures indicate important modifications to the hydrograph under the influence of climatic variation. Each component of the hydrograph will be examined.

		Scenario			
	1969	1	2	3	4
Snowmelt (m^3 x 10^6)	401	**600** (49.7%)	413 (3.1%)	356 (-12.2%)	**617** (53.9%)
Icemelt (m^3 x 10^6)	62	**88** (41.9%)	70 (13.1%)	**99** (59.8%)	51 (-17.0%)
Rainfall (m^3 x 10^6)	160	**243** (51.7%)	174 (8.5%)	195 (21.7%)	169 (5.6%)
Groundwater (m^3 x 10^6)	644	**953** (47.9%)	679 (5.3%)	679 (5.3%)	884 (37.2%)
Evapotranspiration (mm)	655	719 (9.9%)	676 (3.3%)	719 (9.9%)	655 -
Total Discharge (m^3 x10^6)	1267	**1883** (48.7%)	1335 (5.4%)	1328 (4.9%)	1721 (35.9%)

Table 7.4. Summary of the effects of the climatic scenarios on rainfall, snowmelt, icemelt, groundwater, evapotranspiration and total discharge. Bracketed figures indicate % change from original 1969 calibration.

7.3.3.1. Snowmelt

The main hydrologic component of the Bow River above Banff is snowmelt. Figure 7.7 displays the effect of each scenario on snow accumulation and meltwater production. Climatic scenario 1 increased snowmelt discharge by 49.7%. The higher temperatures result in the ablation period commencing about seven days prior to the 1969 estimate, and total ablation of the snowpack occurs about five days later. The early melt period is much more intense when compared to the 1969 estimate. Peak spring discharge occurs on the same day as estimated in 1969, but is 33.6% greater.

The model does not calculate a drastic modification of the snowmelt hydrograph when forced with climate scenario 2. There was only a 3.1% increase in calculated snowmelt, even though winter precipitation was increased by about 10%. The higher temperatures do not cause spring melt to occur significantly earlier (seven days, as in scenario 1), however, the early snow melt period (julian day 97 to 130) is much more intense (about 40% more per day).

Under the influence of climate scenario 3, estimated snowpack water equivalence for elevation band 4 decreased by 16.8%. Similar results were observed in other bands. The increase in temperature translated to a 12.2% decrease in estimated snowmelt discharge. This is largely the result of the higher temperatures delaying the accumulation season by about two weeks. In addition, the higher temperatures transform early spring and late summer snowfall into rainfall. Without the periodic snowfalls in early spring, albedo decay continues uninterrupted, and thus increases the potential for snow melt. The model estimates snowmelt to begin sixteen days prior to the 1969 calculation (figure 7.7). Essentially, snowmelt occurs more gradually over a longer period of time, and thus peak discharge, occurring on julian day 157, is reduced by 22.3% under the influence of scenario 3.

Scenario 4 (increasing snowfall by 55%) held the greatest influence on snowmelt discharge, increasing it by 53.9%. As temperature is not modified in this scenario, snowmelt commences on the

same day as in the 1969 estimate, however, the snowpack does not completely ablate until roughly twenty days later. Peak melt is 19% greater, and occurs thirteen days later than the 1969 estimate.

7.3.3.2. Icemelt

The results for the icemelt calculations are presented in figure 7.8. Climate scenario 1 delays glacier melt slightly as a result of a deeper snowpack. However, from julian day 170 onwards average daily melt is increased significantly: total yield is 41.9% greater than the 1969 estimate. Climate scenario 2 does not significantly influence the timing of icemelt but does increase total yield by 13.1%. The higher temperatures of climate scenario 3 result in the glaciers being exposed earlier than the 1969 estimate, and thus icemelt begins roughly eight days earlier. The higher temperatures also prolong the melt season into the next hydrologic year. Total yield from icemelt is magnified by 59% under scenario 3. The deeper snowpack calculated by scenario 4 results in a significant delay of glacier melt; from Julian days 130 to 187 icemelt is reduced by 71.2%. The model does not calculate any difference in icemelt for scenario 4 from Julian day 187 onwards.

7.3.3.3. Rainfall

Results of the effect of the climatic scenarios on rainfall are presented graphically in figure 7.9. Increasing winter precipitation heightens rainfall by 5.6%, primarily the result of temperature lapse rates causing rain to occur in the lower elevation bands during snowfall events. Scenarios with higher temperatures (1-3) positively augment estimated discharge from rainfall during spring and autumn. This is because the increased temperatures force the model to transform snow into rain during periods of temperatures near 0°C. Increasing both temperature and precipitation (scenario 1) results in a 51.7% increase in annual yield from rainfall, however June to September rainfall-runoff was only increased by 26.8%.

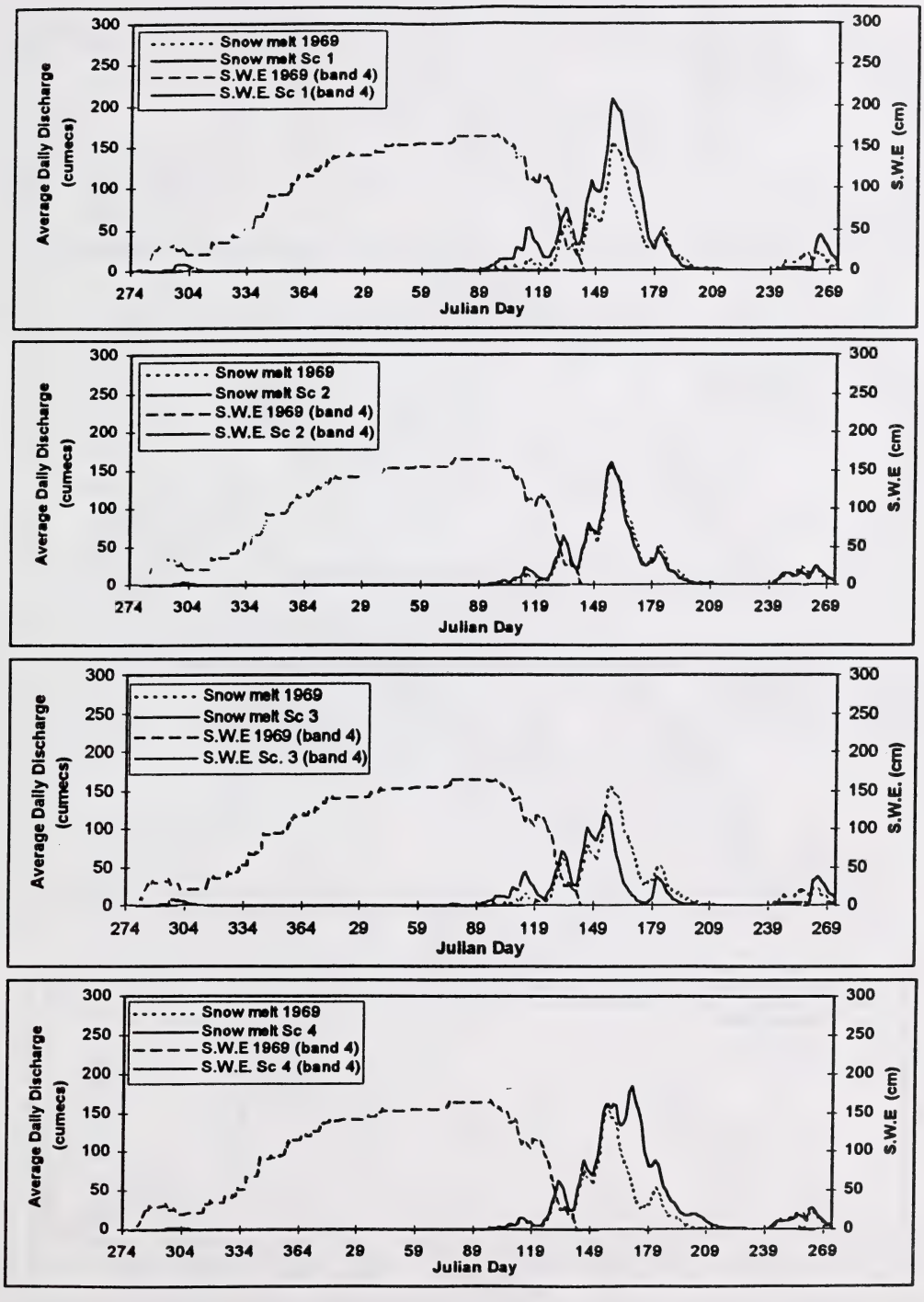


Figure 7.7. Effect of climatic scenarios 1-4 on UBC model estimated snow accumulation and snow meltwater in the Upper Bow Valley. Snowmelt is for entire basin and snow water equivalence (S.W.E.) is for elevation band 4 (2020-2247 m asl)

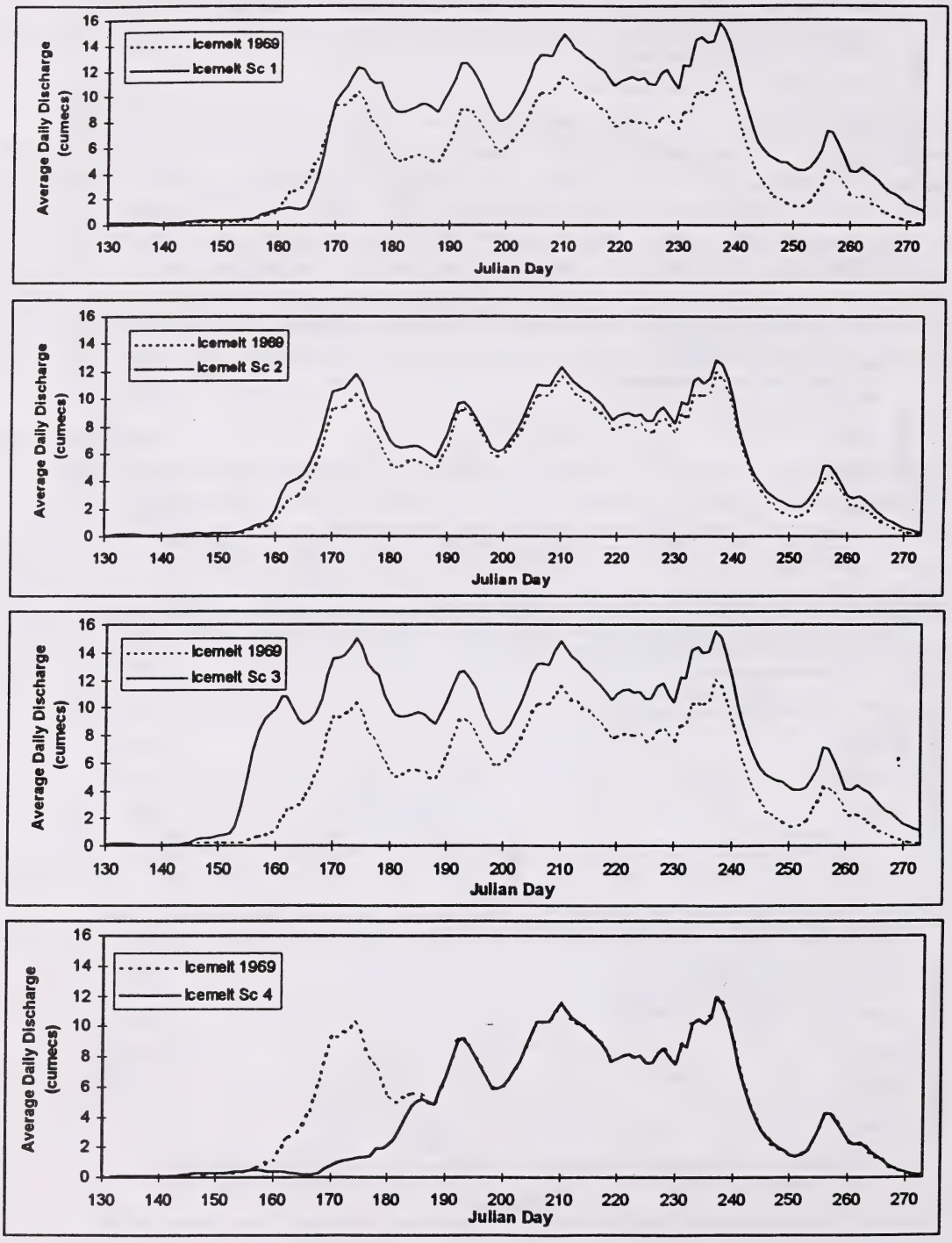
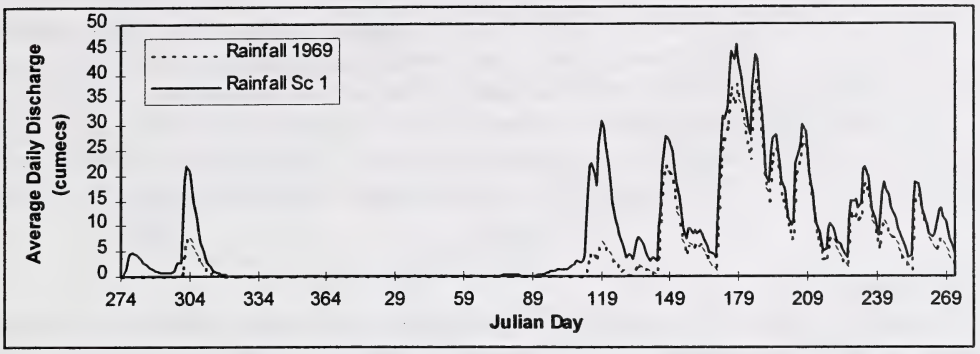
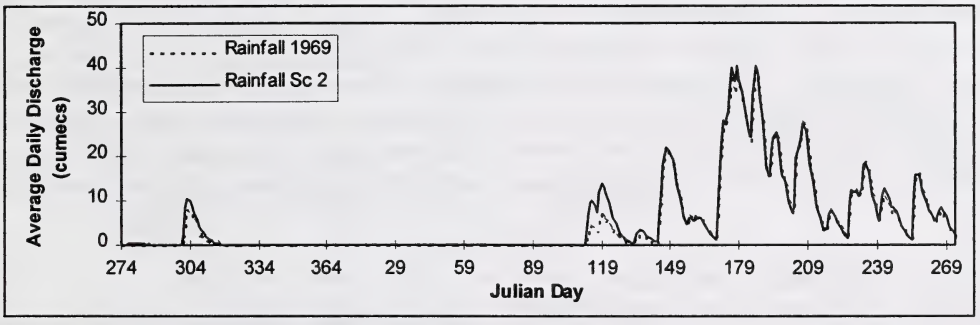
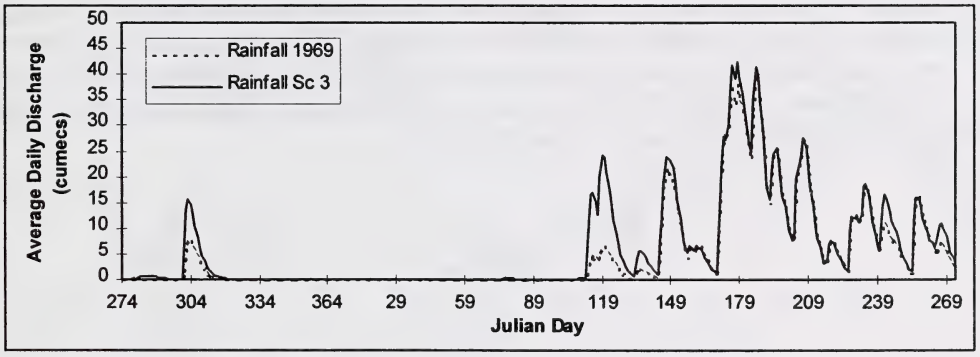


Figure 7.8. The effect of climatic scenarios 1-4 on UBC Model calculated icemelt.







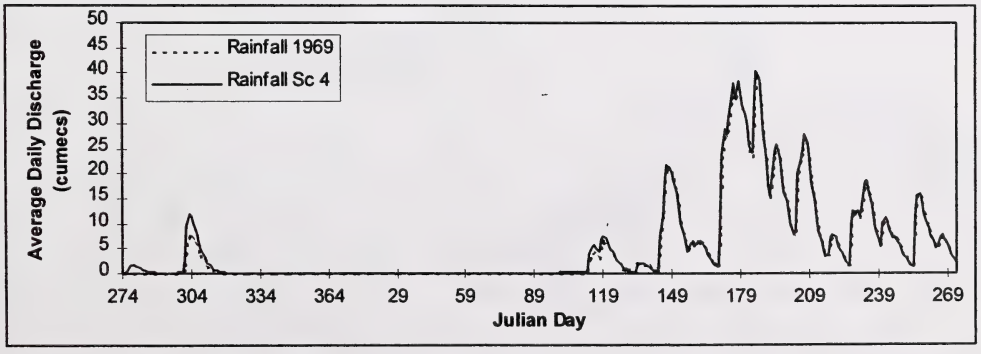


Figure 7.9. Results of climate scenarios 1-4 on UBC Model estimates of discharge from rainfall.

7.3.3.4. Evapotranspiration

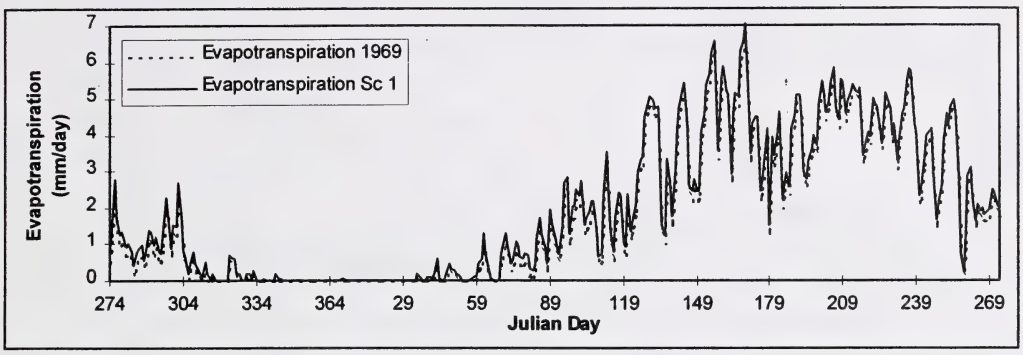
The effects of the climatic scenarios on UBC Model evapotranspiration estimates are graphically displayed in figure 7.10. As evapotranspiration is estimated from temperature alone, increases in precipitation do not cause evapotranspiration feedbacks. The extreme temperature modification of scenarios 1 and 3 cause an evapotranspiration increase of 9.9%. The same relationship is evident when the model is forced by the modest temperature increase of scenario 2. In this case an evapotranspiration increase of 3.3% was generated. The timing of the evapotranspiration increases is comparable throughout the year.

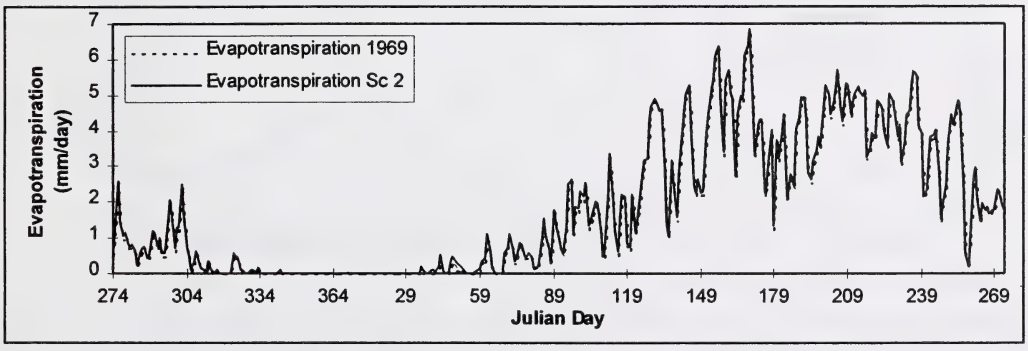
7.3.3.5. Groundwater

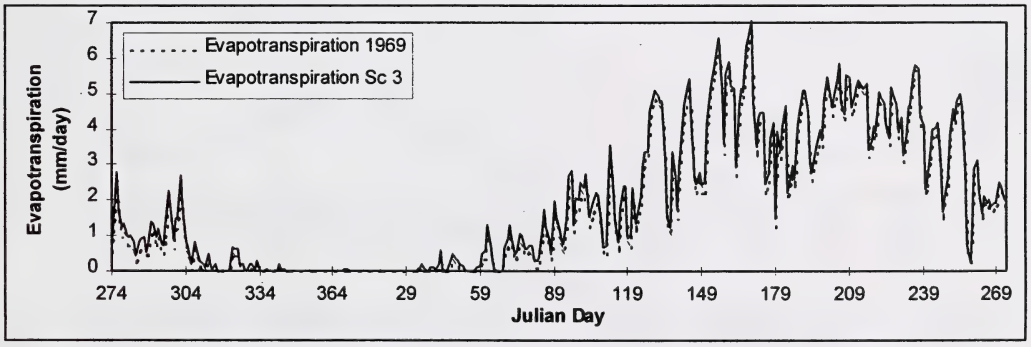
As displayed in figure 7.11, increased snowmelt holds the greatest influence on estimated groundwater (upper and lower combined). A 55% increase in snowfall (scenario 4) translates to a 37.2% increase in groundwater yield; when coupled with an extreme increase in temperature (scenario 1) this value is boosted to 47.9%. The model results suggest that increased precipitation as snow will augment groundwater flows throughout the summer due to enhanced lower (deep) groundwater storage from spring melt, which is routed through the system much more slowly than upper groundwater. Higher temperatures tend to expedite groundwater flows: climate scenario 3 caused spring groundwater augmentation to commence twenty two days prior to the 1969 estimate, resulting in a suppression of summer groundwater flow.

7.3.3.6. Bow River Discharge - Total Yields

Climate scenarios that significantly increase winter precipitation have the greatest influence on Bow River above Banff discharge (figure 7.12): peak flow is accentuated and average daily discharge is augmented through the summer months by groundwater reserves. Extreme increases in temperature accelerate snowmelt and intensify and prolong glacier melt, which ultimately works towards moderating river flow over a longer period of time. Minor adjustments to both temperature and precipitation (scenario 2) do not lead to major variations in estimated total discharge.







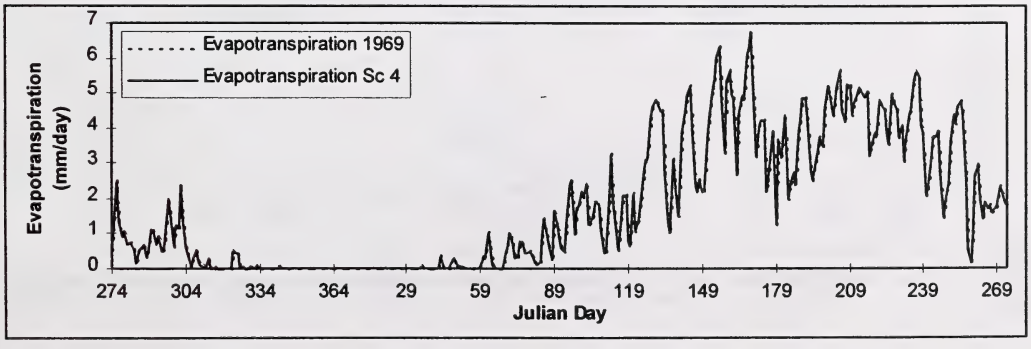
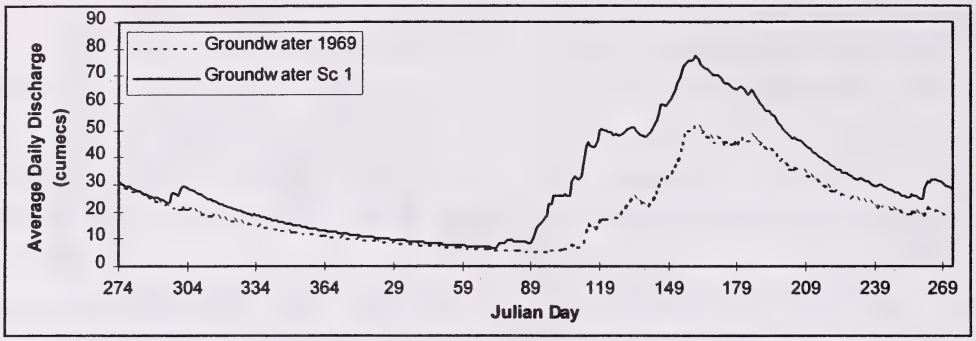
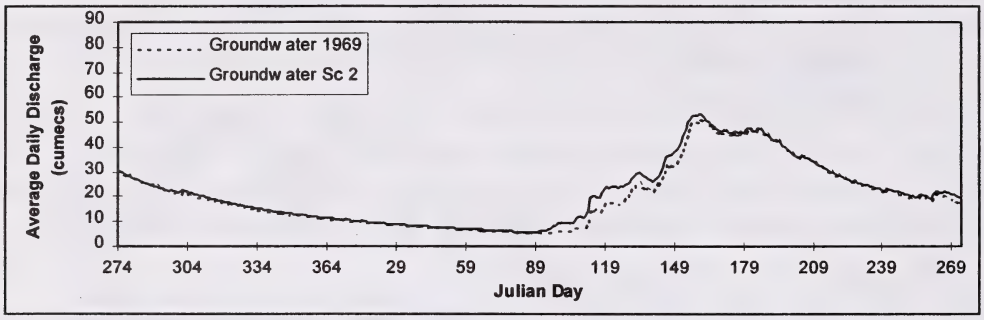
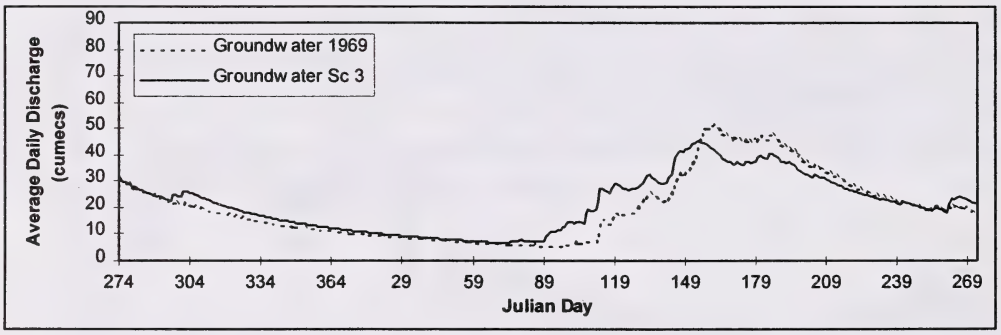


Figure 7.10. Effect of climatic scenarios on UBC Model evapotranspiration estimates for the Upper Bow Valley.







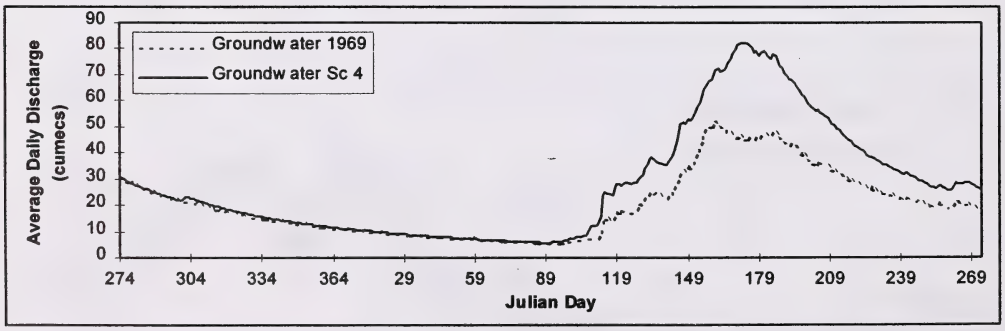


Figure 7.11. Effect of climatic scenarios 1-4 on UBC Model estimates of groundwater discharge (upper and lower combined).

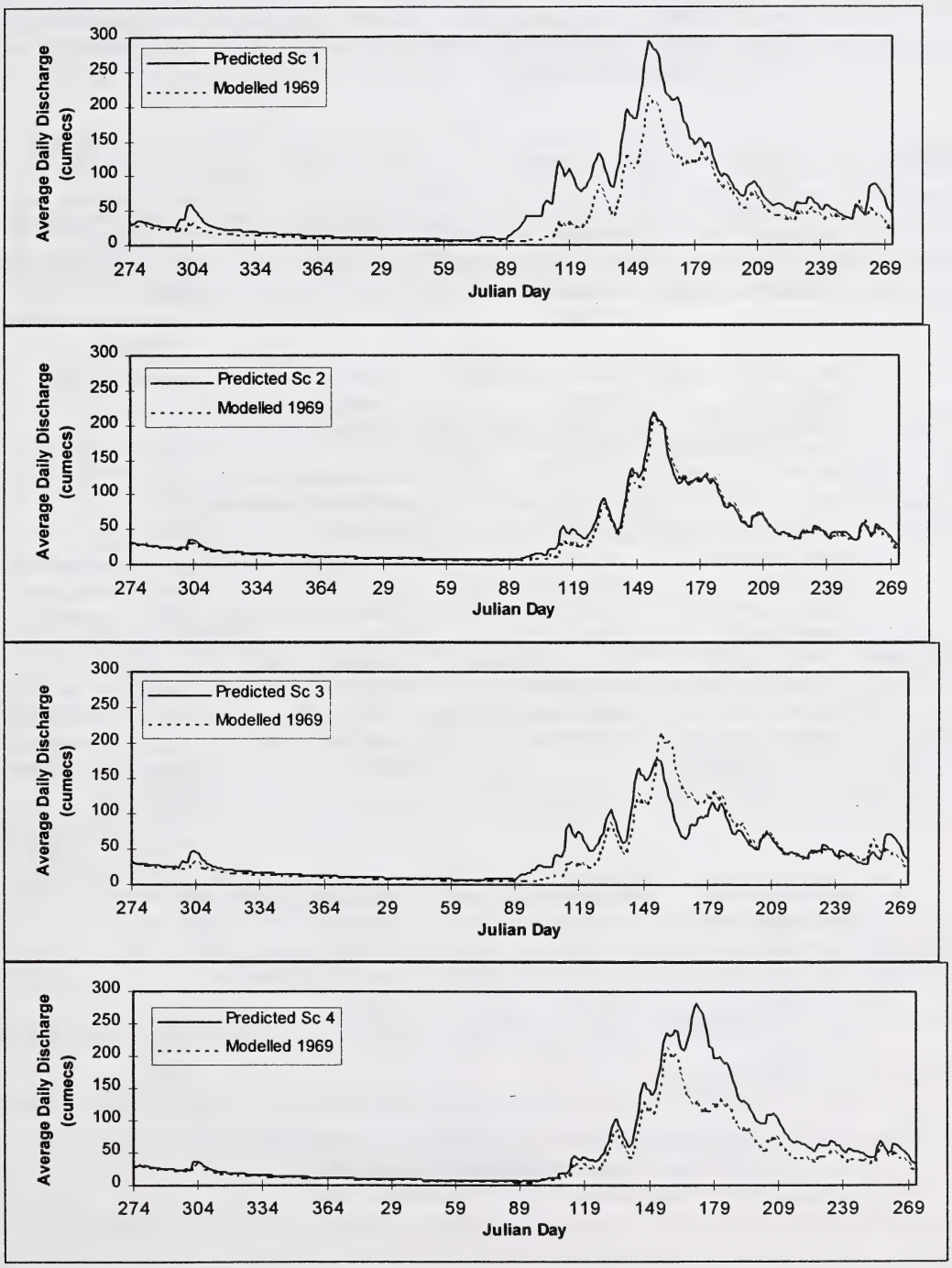


Figure 7.12. Results of the climatic scenarios 1-4 on UBC Model estimates of total discharge.

8. Conclusions and Key Findings

A summary of conclusions of the effects of climate scenarios 1-4 on various components of Upper Bow River discharge is presented in table 8.1.

Process	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Snowmelt	• **much earlier snowmelt** • **large increase in peak melt and yield**	• slightly earlier snowmelt • slight increase in yield • very little increase in peak melt	• much earlier snowmelt • decrease in snowmelt yield and peak melt	• **greatest increase in snowmelt** • **large increase in peak melt** • **peak melt occurs later in spring**
Icemelt	• **significant increase daily icemelt** • **icemelt is slightly delayed but continues longer**	• small increase in daily icemelt • timing not significantly effected	• **greatest influence on icemelt; daily melt increased by about 20%** • **icemelt starts much earlier and continues into Oct.**	• icemelt is delayed
Groundwater	• **great increase in groundwater flow from snowmelt contributions** • **groundwater recharge starts much earlier** • **recession flows are heightened from deep groundwater flows**	• very little change in groundwater flows • recharge starts slightly earlier and is more intense during early spring, but returns to calibrated values during the summer	• slight increase in total yield • recharge begins earlier and is more intense during early spring • recession flow begins earlier, and peak groundwater flow is reduced	• **great increase in groundwater flow from snowmelt contributions** • **start date for recharge is not greatly affected, but recharge is more intense and continues longer** • **recession flows are heightened from deep groundwater flows**
Evapo-transpiration	• increase in annual evapotranspiration losses (10%) • no significant variance in timing	• slight increase in annual evapotranspiration losses (3.3%) • no significant variance in timing	• increase in annual evapotranspiration losses (10%) • no significant variance in timing	• no change
Total Discharge	• **greatest influence on total yield** • **almost 50% increase**	• small increase in total yield (5.4%)	• small increase in total yield (4.8%)	• **large increase in total yield** • **37% increase**

Table 8.1. Summary of conclusions of the effects of climate scenarios 1-4 on various components of Upper Bow River discharge. Those highlighted indicate important changes.

8.1. Snowmelt

As snowmelt is the dominant hydrologic factor in the Upper Bow Valley, the UBC Model predicts that variations in winter precipitation regime will have the greatest effect on the hydrograph. GCMs estimate that winter precipitation may increase by as much as 50% in the Canadian Rockies as a result

of an enhanced Pacific orographic effect. If this predicted trend becomes reality, then glacier melt will be delayed into the spring and summer (depending on the temperature regime) as the snowpack aquifer will insulate the glacier surface.

8.2. Icemelt

The model suggests that the reduction of glacier area will lead to a decrease in the potential for glacier runoff. Increases in temperature will allow glaciers to produce more meltwater per unit area, however, even an extreme temperature increase cannot make up for significant glacier loss. In addition, the model suggests a non-linear relationship between glacier area and meltwater production: glaciers may become less sensitive to meteorological forcings as they ablate to higher or more sheltered regions of the basin.

8.3. Groundwater

The model predicts that a significant consequence of a warmer climate is a shift in the winter/summer groundwater ratio. Higher temperatures cause earlier snowmelt, which in turn results in earlier groundwater recharge to the unconfined aquifer. This causes groundwater flow to be reduced during the summer, as snow meltwater is passed through the aquifer earlier. This feedback combined with a reduction in icemelt contribution can have potentially serious negative effects on summer discharge, when water is needed most.

8.4. Evapotranspiration

The model also suggests that a warmer climate will increase evapotranspirative losses by as much as 10%, however, problems associated with the evapotranspiration routine limit the confidence of this conclusion. It is logical to assume that a warmer climate will indeed increase rates of evapotranspiration, therefore causing greater stress on the summer water budget. Research into the relationship between stomatal resistance of plants and increased CO_2 coupled with the application of a physical evapotranspiration model is needed to estimate the climatic sensitivity of evapotranspiration in the Upper Bow Valley.

8.5. Suggestions for Improvement

In the late 1970's and early 1980's, hydrologic model outputs were often considered indubitable. Experience has taught policy makers and modellers to take a critical stance when interpreting model estimations, (even despite the great advances made in modelling over the past decade). The following section is dedicated to critiquing the methodology used in this study and provides suggestions for improvement.

8.5.1. Application of a Physically-Based Model

The use of the UBC Model for such a study can be criticized on the basis that it is not a highly physical model. The predictive power of a quasi-physical model is inherently limited as a result of the calibration process and the coarse parameterization of hydrological and climatological processes. To a large extent, the model is history-based, and thus deviations from the observed calibration data transcend the model's predictive capability. It addition, the UBC Model does not consider many of the non-linear processes and feedbacks functioning within and between the hydrological and climatological parameters.

Ideally, a physically-based, data intensive model should be used for future analysis. By applying such a model, a better representation of the sensitivity of the physical processes functioning within the basin should be achieved. However, the collection of calibration data for a data-intensive model for a

macro-scale (over 1500 km^2) basin is a tremendous task; several years of detailed reference data (hydrological, meteorological, pedological, and hydrogeological) would have to be collected over a large area. In addition, physical models are generally more suited to smaller basins because of the intense parameterization involved (Singh, 1988), with the exception of the SLURP model (Kite and Kouwen, 1992). Thus it is suggested that smaller, representative basins be examined in finer detail.

Both a nival and glacierized basin should be studied, as the hydrological characteristics of both types of basins are distinct. Prime candidates could be the glacierized Hector basin and the nival Brewster Creek basin. Reducing the spatial scale would allow for a more detailed physical analysis of the hydrological and meteorological processes prevalent, and would reduce cost and effort. The results from such a study can be used as a surrogate for the entire basin by applying a landcover classification.

8.5.2. Use of Satellite Imagery

As Brugman, et al. (1995) point out, it is highly recommended that satellite imagery be incorporated into the glacier melt modelling process to account for changes in ice extent. Satellite data for the Upper Bow Valley should be collected from as early as possible and be subject to a land cover classification to document the rate of glacier recession. This classification should then be combined with a Digital Elevation Model (DEM) of the entire basin that can be used for future monitoring. Franklin (1991) presents a simple yet effective methodology for combining remote sensing data with DEMs for mountainous terrain.

8.5.3. Establishment of a High Altitude Meteorological Station

Many of the problems experienced with this analysis could have been avoided if a high altitude meteorological station was operational in the Upper Bow Valley. Such a station would be invaluable for estimating the orographic enhancement of precipitation and the persistence of temperature inversions - two key elements of hydrologic modelling. B.C. Hydro has significantly improved its operational flow forecasting efficiency using the UBC Watershed Model by installing both valley and high altitude meteorological stations (Nixon, 1997). The highest station in the Upper Bow Valley, which extends to over 3500 masl in some areas, is located at 2200 masl in Sunshine Village near Banff. Ideally, a new high altitude station should be established much higher and in a more central location, preferably on the apex of several watershed boundaries so results can be directly applicable to more than one sub-basin. Data from this station would certainly improve model output.

8.5.4. Use of Isotopic Analysis to Verify Model Output

The results of isotopic analysis of river discharge can be used to separate the hydrograph to its fundamental components of snowmelt, icemelt, rainfall, and groundwater. Isotopic analysis of Bow River at Banff discharge, currently being conducted by Hopkinson and English of the Cold Regions Research Centre, Wilfrid Laurier University, should be employed to corroborate model output. Hydrograph separation using oxygen-18 and tritium can provide insight into the contribution of ice melt to the Bow River, and thus can be used as a source of comparison with hydrological model predictions.

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